

FINAL REPORT

Development of Scaling Algorithms and Economic Evaluation for Non-Thermal Plasma Reactors – Adsorbant/Catalyzer Hybrid System for Control of NO_x Released During Army and Related U.S. Department of Defense (DOD) Operations
Contract No. DAAL01-98-P-0741

K. Urashima, S.J. Kim and J.S. Chang
Department of Engineering Physics
McMaster University
Hamilton, Ontario, Canada L8S 4L7
(905) 525-9140, ext. 24924
FAX: (905) 527-5222

for

Dr. Andrzej W. Miziolek
U.S. Army Research Laboratory
AMSRL-WM-PC
Aberdeen Proving Ground, MD 21005-5066
U.S.A.
DSN: 298-6157
COM: (410) 278-6157

October 31, 1998

DTIC QUALITY INSPECTED 4

19991202 048

EXECUTIVE SUMMARY

Objectives of the Project

The objective of this task is to develop economic evaluation and scaling algorithms for non-thermal plasma adsorbant/catalyzer hybrid systems which are used to remove NO_x from the air stream during army and related U.S. Department of Defense (DOD) operations. These systems need to be fully economically evaluated with respect to destruction efficiency, energy efficiency, electrical operating characteristics, and final product analysis based-on bench scale tests and numerical analyses so that the detailed models and experiments run at ARL can be correlated with the global apparatus behaviour and scale-up.

The specific original tasks are:

- (1) Economic evaluations for the non-thermal plasma - adsorbant/catalyzer hybrid systems for jet engine test cell (JETC) conditions.
- (2) Characterize non-thermal plasma - adsorbant/catalyzer hybrid systems proposed by ARL for operating behaviour with NO_x in air streams. Characterization tests will be performed for one selected type of each adsorbant and catalyzer based on literature searches and manufacturer's data.
- (3) Construct De- NO_x devices scale-up procedures for bench scale to pilot scale tests proposed by ARL.

Due to the request from DOD, the above original tasks are slightly modified as follows:

- (1) Economic evaluations for the non-thermal plasma systems for JETC and cruise missile test cell (CMTC) condition must be conducted and compared with conventional wet-scrubber-SCR systems;
- (2) Characterize non-thermal plasma-catalyzer hybrid system for NO_x and SO_2 treatment in air streams containing hydrocarbon. Conduct literature search for catalyst and adsorbents.
- (3) Construct JETC/CMTC flue gas non-thermal plasma treatment system scale-up procedures and conduct preliminary conceptional design of pilot scale test system.

Conclusions and Recommendations

In order to develop scaling algorithms and economic evaluations for non-thermal plasma reactors with and without adsorbants/catalysts for the control of NO_x from jet engine and cruise missile test cells, an existing SUENTP code (Kim and Chang, 1998) was modified - SUENTP-J and the following conclusions and recommendations are obtained:

- (1) For the jet engine test cell (JETC) condition of 10^6 scfm ($1.62 \times 10^6 \text{ Nm}^3/\text{h}$) flow rate, the conventional SCR/wet scrubber system costs 2 to 3 times more than any of the evaluated non-thermal plasma techniques. The cost of an electron-beam/electrostatic precipitator (ESP) system is 20-30% more than pulsed corona or corona shower system with ESP;
- (2) For the JETC condition, SCR can be a stand-alone system without a wet scrubber if we do not remove SO_2 . However, the life of SCR becomes shorter (less than half) with sulphur poisoning and an additional ESP system is required. Cost estimation for this SCR/ESP system is only slightly lower ($\sim 10\%$) compared with the SCR/wet scrubber system;
- (3) For the cruise missile test cell (CMTC) condition of 6×10^4 scfm ($10^5 \text{ Nm}^3/\text{h}$) flow rate, the conventional SCR/wet scrubber system costs 2 to 2.5 times more than pulsed corona/ESP or

corona shower/ESP system. However, the cost is 40% more than that of an electron beam/ESP system.

- (4) In order to estimate more accurate non-thermal plasma system costs for JETC and CMTC conditions, much larger pilot plant tests, up to 200 to 1000 Nm³/h, are required;
- (5) In order to reduce more costs, a non-thermal plasma-adsorbant/catalyzer hybrid system should be tested. Based on preliminary experimental work, the cost reduction is as much as 20 to 30% of stand alone non-thermal plasma systems.

An experiment also conducted for non-thermal plasma (corona shower system)-catalyst hybrid system to treat simulated JETC flue gas and the following concluding remarks are obtained:

- (1) SO₂ can be 100% removed by injections of NH₃, CH₄ or NH₃/CH₄ mixture generated radicals;
- (2) SO₂ removal increases with increasing applied voltage and significant catalytic reduction/adsorption effects are observed;
- (3) Heating of catalyst shows no significant effects on SO₂ removal for the NH₃ injections in the present range of gas temperature ($T_g = 228K$) but reduce capability of catalyst for CH₄ injections;
- (4) NO_x removal significantly enhances NO_x removal for NH₃ injections at room temperature with catalyst due to the NO₂ reductions but NO_x removal decreases with gas temperature;
- (5) NO_x removal increases with increasing applied voltage and up to 65% of NO_x removal rates are observed in hybrid systems with NH₃ injections;
- (6) NO_x removal increases with increasing applied voltage under CH₃ or CH₄/NH₃ mixture injections and up to 42% removal rate is observed. However, no significant catalytic reaction or gas temperature effects were observed.

Based on the economic evaluations and an experimental test, the conceptual design of the pilot plant study was proposed as follows:

- (1) Approximately 340 Nm³/h JETC flue gas will be by-passed from the main flue gas and treated by non-thermal plasmas;
- (2) Non-thermal plasma JETC flue gas treatment test facility consisted of corona shower reactor and electrostatic precipitator, where catalyst will be considered as options;
- (3) Five-section corona shower system size is (140×60×120 cm) with 14 flow channels, and operated by 6 kW dc power supply (40 kV×150 mA maximum);
- (4) Five-section ESP size is (150×60×80 cm) with 30 flow channels and operated by 6 kW dc power supply (40 kV×150 mA maximum); and
- (5) Pressure drop, NO_x, SO_x, VOC concentrations will be monitored at inlet and exhaust of pilot plants.

Acknowledgements

The authors wish to thank L. Rosocha, T. Ito, M. Matsuoka, T. Nomura and A.W. Miziolek for valuable discussions and comments. Authors also thanks Z. Tong, T. Nomura and P.C. Looy for technical assistants.

TABLE OF CONTENTS

Executive Summary

Part 1 SUENTP-J Code Simulations of Scale-up and Economic Evaluation of Non-Thermal Plasma Technology for Exhaust Gas Emission Control of Jet Engine Test Cells

- 1.1 Introduction
- 1.2 Non-Thermal Plasma Technology
- 1.3 Scale-up and Economic Evaluation Code
- 1.4 An Example Based on Existing Pilot Plant Tests
- 1.5 Concluding Remarks

Part 2 Acid Gas Removal Characteristics of Corona Radical Shower-Catalyst Hybrid System for Treatment of Jet Engine Test Cell Flue Gases

- 2.1 Introduction
- 2.2 Experimental Apparatus
- 2.3 Experimental Results Without Catalysts
- 2.4 Experimental Results of Hybrid Systems
- 2.5 Concluding Remarks

Part 3 Preliminary Conceptual Design for Pilot Plant Test for Plasma Jet Engine Test Cell Flue Gas Treatments

- 3.1 Introduction
- 3.2 Proposed Design and Specifications
- 3.3 Recommendations

Appendix Review of Catalysts/Adsorbants for Pollution Control

A.1 Introduction

A.2 List of Catalysts

A.3 Concluding Remarks

PART 1.

SUENTP-J CODE SIMULATIONS OF SCALE-UP AND ECONOMIC EVALUATION OF NON-THERMAL PLASMA TECHNOLOGY FOR EXHAUST GAS EMISSION CONTROL OF JET ENGINE TEST CELLS

ABSTRACT

Computer code (SUENTP-J) to predict scale-up and economic evaluation of several eligible non-thermal plasma processes for air pollution control - electron beam process, pulsed corona process, and corona radical shower process - was developed for a commercial power plant. This code was written in spread sheet type format (MS Excel) and visual basic for application and comprise a data input procedure, a scale-up (design) procedure, an economic calculation procedure, and an output procedure. Data obtained from pilot plant tests are input with general data so that they might lead to the conceptual design data of commercial plants by scale-up procedure. In the economic evaluation procedure, the total capital investment and the total annual cost are examined. The total capital investment comes into the indirect annual cost as the item of capital recovery. The levelized cost and the levelized busbar cost are shown in the output table. An example calculation was presented to evaluate the cost of three non-thermal plasma systems and the results were compared with a conventional wet-scrubber/selective catalytic reduction combined system.

1.1 INTRODUCTION

Several eligible non-thermal plasma technologies are in the stage of commercialization, and more recently, a several small scale commercial systems based on pulsed corona and electron beams

are operating (Li et al, 1997). At this moment, their economic evaluation is requested not only for the selection of the most proper technology according to the subject facility, but also for the readjustment of future R&D direction of those technologies. In the past, there were a few economic evaluation works on NTPs. The Japanese Mechanical Industry Association and Energy Engineering Institute (1991) compared the types of De-SO_x and De-NO_x facilities from a coal fired power plant - the conventional wet-scrubber/selective catalytic reduction combined process, the electron beam process, and pulsed corona process. However, they evaluate their costs for only one case of 250MW power plant. Most other works are only for electron beams (Frank and Hirano, 1990; Tokunaga et al., 1995) or pulsed corona (Civitano, 1992) processes. Bartoszek et al. (1998) outlined economic evaluation methods for advanced reburning De-SO_x and De-NO_x processes based on thermal and non-thermal plasmas and proposed to use energy yield (reduced amount of acid gas [g]/input power [kWh]) for the accurate calculation of economic evaluations for plasma processes.

The non-thermal plasma (NTP) techniques are still not optimum and economic evaluations for commercial plants are rare. However, we have made an effort to estimate their economics as exactly as possible by using the most up-to-date information. The most important objective of an economic evaluation is to decide which system is most effective for the given conditions in terms of the flowrate of exhaust gas, initial concentration of NO_x, SO_x and the other emissions, space requirements, type of pollutant gases, etc. In this work, a simulation code named SUENTP-J is developed to evaluate and analyze scale-up procedures and economics for conceptual design of the three leading non-thermal technologies for commercial gas cleaning systems.

1.2 NON-THERMAL PLASMA TECHNOLOGY

Two different approaches are used for plasma gaseous pollution control. The first approach (direct method) is to treat flue gases directly by plasmas (mixture of electrons, ions and free radicals). The second approach (indirect method) is activating reducing or oxidizing gases by plasmas externally and injecting into flue gases. In the first approach, an input energy may be lost to activate unwanted flue gas components such as N_2 , O_2 , CO_2 , etc., and the second approach requires suitable long life free radicals for pollutant gas treatment.

Non-thermal plasma direct treatment reactor can be divided into three different plasma sources as follows:

1. DC or pulsed corona reactor – (a) pin-plate; (b) corona torch; (c) capillary tube; and (d) wire-tube/wire-plate reactors.
2. Barrier discharge reactors – (a) silent discharge (b) surface discharge; (c) packed bed; and (d) superimposed barrier discharge reactors.
3. Electron beam reactors.

In order to avoid corona-to-spark discharge transitions, high gas flow or pulse applied voltage operations are used for corona devices, while a dielectric barrier is placed in the front of the electrodes in barrier discharges. The mean electron temperature for the corona or barrier discharge devices is 1 to 10 eV, while the electron beam devices are a few 100 keV. Indirect non-thermal plasma reactors currently developed are (a) corona radical injection devices and (b) corona shower system. DC or pulse power supplies are used for these retrofit devices and often these devices are used together with direct plasma treatment devices to enhance pollution gas treatment, i.e. hybrid concepts.

In this work, a wire-plate pulsed corona reactor, a corona shower system, and an electron beam reactor are selected for scale-up and economic evaluation algorithm development.

1.3 SCALE-UP AND ECONOMIC EVALUATION CODE

Features of the Code

The code SUENTP-J is written in Microsoft (MS) Excel and Visual Basic for Application (VBA). MS Excel is very convenient for treating considerable amounts of data and making charts from the results as a spread sheet type software. VBA is a kind of computer language, which might make this code more user-friendly interactive one. VBA is useful for the calculation of multiple conditions and the drawing of charts automatically.

This SUENTP-J code consists of an Input Data part, a Scale-up Calculation part, an Economic Calculation part, and an Output part VBA connects. Fig. 1.1 shows the simplified flow chart of this code. This code can be used for various emission sources, but it is focused on the jet engine test cells in this work.

Data Input Procedure

The input data comprise two parts: common input data and input data from pilot plant tests. When the code file is opened first on MS Excel, a data sheet becomes available. This sheet includes common input data displayed in the first column of Table 1.1. Some of these input data, which are written in bold characters are some important parameters for sensitivity tests of each NTP system such as the capacity of the engine, initial NO or SO₂ concentration, removal rate of NO_x or SO_x, etc. Users can choose a variable with a set of values for a series of calculations. Then the calculations of scale-up and economic evaluation are carried out using those values. The others are general data for

emission source control, and unit prices, which are supposed to be adapted to all NTP processes. They must be input in this sheet by a user.

The Scale-up Procedure

Non-thermal plasma for emission control is accompanied by very complicated physical and chemical phenomena so that it is difficult to analyze theoretically. Therefore most design data should be obtained from experimental studies. In this work, the principal design data will be acquired from pilot plant experiments. Then these data are adopted as commercial plant design data directly.

Detailed design data as revealed in the second column of Table 1.1, which are obtained from the pilot plant experiments, and input into the sheet of the scale-up design procedure for each NTP process. These data are essential for the economic evaluations as well as for the scale-up design. Experimental values of energy are especially important since they affect not only the power supply capital cost, which is the most expensive among the capital costs, but also the electric power consumption cost which is one of the highest items in the annual cost. The consumption rate of power and chemicals such as NH_3 and hydrocarbons, are also quite important factors in the economic evaluation of non-thermal plasma systems for the removal of gaseous emissions.

This scale-up design sheet shows both of these input values and the calculated output values in the third column of Table 1.1. Some of output results are used to calculate the capital cost and the others the annual cost.

The Economic Calculation

The economic evaluation follows Vataavuk's procedure (Vataavuk, 1990). The total capital investment is composed of depreciable and nondepreciable investment. The total annual cost is the

sum of direct annual cost and indirect annual cost. If there is any recovery credit such as material and energy, the total annual cost could be reduced by this amount. The total capital investment comes into the indirect annual cost through the item of capital recovery. The important items of total capital investment and total annual cost are shown in Table 1.2. In this work, the period of construction is ignored, which is called "overnight construction". The inflation rate is considered as used in most utility cost evaluations. However, no tax is included.

As shown in Table 1.1, the calculated design values in the scale-up part for commercial power plant are related to estimated direct capital cost, and others are estimated direct annual cost. The direct capitals costs of primary equipment - reactor, power supply, and dust collector - are calculated using the input data obtained from existing bench, pilot or demonstration plants using the power factor model (Vatavuk, 1990; Bartoszek et al, 1998). The cost-capacity relationship in this estimate is based on the power factor model. The cost capacity factor is assumed in the range from 0.1 to 1.0. Generally, the factor is a round 0.6-0.7 for the large plants, and 0.3-0.4 for the pilot plants (Frank and Hirano, 1990; Bartoszek et al, 1998).

The economic estimation can allocate credits for the sale of by-products. It is expected that most of non-thermal plasma systems using NH_3 will produce a good fertilizer of ammonium sulfate and nitrate salts. As Frank and Hirano (1990) proposed, a system design which yields saleable sulfurous by-products may be essential to the application of flue gas treatment. Levelized costs or levelized busbar costs can be obtained from the total capital investment and the total annual costs being levelized by economic data such as a depreciation period, an interest, and salvage rate. The detailed economic procedure to get the levelized cost or levelized busbar cost can be obtained from EPRI Reports (EPRI, 1983; 1991).

Table 1.2. Items of Total Capital Investment and Total Annual Cost

Total Capital Investment (TCI)	Total Annual Cost (TAC)
Total Capital Investment (TCI) = DI + NDI Depreciable Investment (DI) Total Direct Cost - Site Preparation - Buildings - Purchased Equipment Cost - Direct Installation Cost Total Indirect Cost - Engineering and Supervision - Construction and Field Expense - Construction Fee - Start-up - Performance Test - Contingencies Offsite Facilities Nondepreciable Investment (NDI) - Land - Working Capital - Salvage	Total Annual Cost (TAC) = DAC + IAC - RC Direct Annual Cost (DAC) -Raw Materials -Utilities -Waste Treatment/Disposal -Labor -Maintenance Materials -Replacement Parts -Payroll Overhead Indirect Annual Cost (IAC) -Capital Recovery/Depreciation -Plant Overhead -Insurance -Administrative Charge Recovery Credits (RC) -Materials -Energy

Variable Data Contents

Input Data Control											
Variable Data											
Initial NOx ▼											
Variable	Gas Flowrate	Initial NOx	NOx Removal Rate	Initial SOx	SOx Removal Rate	Inlet Temp.	Additional Gas SR				
Unit	Nm3/hr	ppm	%	ppm	%	C	-				
	1.00E+06 ▼	36 ▼	70.0% ▼	4.59 ▼	95.0% ▼	25 ▼	1.5 ▼				
(Default)	6.80E+06	36	80.0%	4.59	95.0%	80	1.0				
Data	1.20E+07	100	90.0%	50.00	100.0%	200	3.0				
	1.00E+07	80	70.0%	30.00	90.0%	150	2.5				
	3.00E+06	50	60.0%	20.00	80.0%	120	2.0				
	1.70E+06	30	50.0%	10.00	70.0%	100	1.5				
	1.00E+06	20	40.0%	7.00	60.0%	50	1.2				
	5.00E+05	10	30.0%	5.00	50.0%	40	1.1				
	1.00E+05		20.0%	2.00		25	0.9				
	1.02E+04						0.8				
							0.7				

Output

The output of SUENTP-J consists of tables and charts. The table output including the items shown in Table 1.2 is very easy to use because it is a simple spread sheet. Another advantage of this type of output is that the output can be produced without running the program as soon as the input is changed. VBA produces charts as well as tables automatically carry out the calculation for a set of each important parameters.

1.4 AN EXAMPLE BASED ON EXISTING PILOT PLANT TESTS

Plant Test Data for Code Input

To obtain a set of pilot plant test data from non-thermal plasma technology for economic evaluations is difficult, since only electron beam (EB) technology has the experience of several pilot or commercial plants to provide baseline engineering data. Pulsed corona (PC) and corona shower (CS) technology do not have enough data for commercialization yet. Another reason is that even rare data from pilot or commercial plants will not be available to the public, since companies concerned the loss of important information to their competition.

Nevertheless, at this moment this economic evaluation must be made to inform the public about the possibility of which system is most profitable for a given emission resource. Therefore, this work tries to evaluate the cost of three non-thermal systems, compared with a conventional wet-scrubber/selective catalytic reduction and/or selective catalytic reduction/electrostatic precipitator systems although the experimental conditions of emission removal are slightly different as shown in Table 1.3.

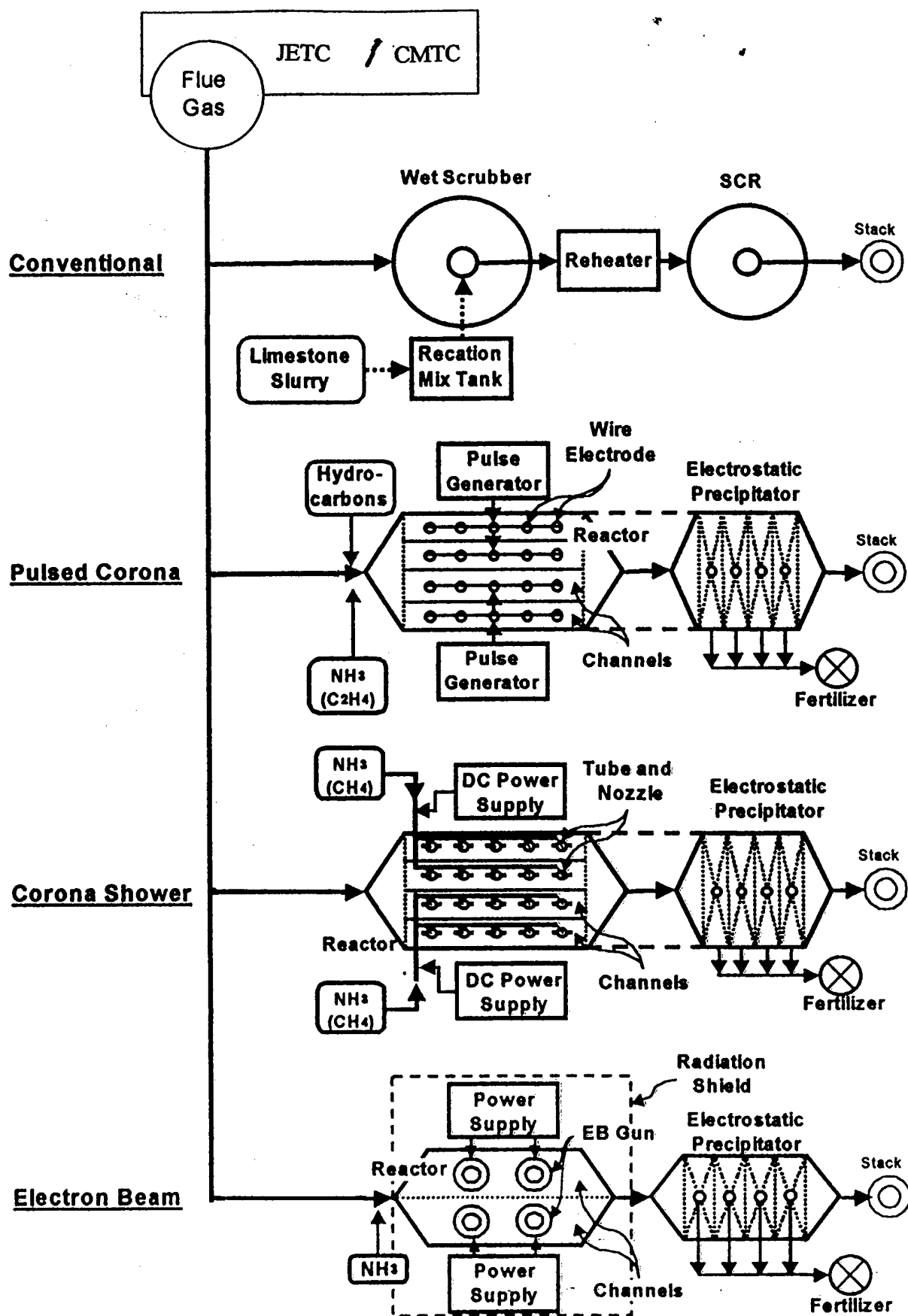


Fig 1.2 Block Diagram of Considered DeSOx and DeNOx Systems

Fig. 1.2 is the block diagram of the considered De-SO_x and De-NO_x systems, as mentioned above. It is assumed that the exhaust gas from the Jet engine test cell reaches thus plasma processes after passing through the main electrostatic precipitators.

Table 1.3 The emission removal conditions of each system for example calculation*.

ITEM	UNIT	Pulsed Corona ¹	Corona Shower ²	Electron Beam ³	Conventional ⁴
Object		JETC	JETC	Undersea Tunnel	Coal Power Plant
Initial NO Concentration	ppm	36	40	10	300
NO _x Removal Rate	%	56	90	70	80
Initial SO ₂ Concentration	ppm	4	4	1	3,050
SO _x Removal Rate	%	90	95	95	90
Energy Yield**	g-NO/kWh	20	1	19.1	-
Experimental Scale	Nm ³ /h	600	12	40,000	1.9×10 ⁶

* Data obtained from 1. Haythornthwaite et al, 1997; 2. Matsuoka et al, 1997; 3. Ebara Co., 1998; 4. EPRI, 1983; JMIA-EEI, 1991.

** Note : All electric power is assumed to contribute to the removal of NO_x.

Discussion

Fig. 1.3 displays the results of a sample calculation for various flue gas flow rates, where 10⁶ scfm (1.62×10⁶ Nm³/h) and 6×10⁴ scfm (10⁵ Nm³/h) are corresponding to JETC and CMTC flue gas flow rates, respectively. As mentioned above, it is very hard to compare the results of this sample calculation because the input conditions of each process are different from each other.

Although they are not disclosed in this figure, the costs of the electron beam guns and pulsed generators had the majority of the total capital costs of EB process and PC process, respectively.

Fig.1.3a Common Input Data of Scale-up and Economic Evaluation
for Jet Engine Test Cells

Source Data									
Plant Type		Jet Engine Test Cell							
Gas Flowrate	Qgas	Nm3/hr	1.00E+06						
Fuel			JP-5						
Capacity Factor	Ruse	%	80						
Gas Composition									
N2	CN2	%	80.98						
CO2	CCO2	%	0.50						
H2O	CH2O	%	0.50						
O2	CO2	%	18.00						
Density(Normal)	Dgas	kg/Nm3	1.283						
Exhaust GasTemp.	Tgas	C	25						
NTP In Temp.	TNTPin	C	25						
Pressure	PRgas	mmAq	720						
Emission Data									
Emission		Inlet Concentration			Outlet Concentration			Removal Efficiency	
NOx	CNOx	ppm	36.00	Cout_NOx	ppm	10.80	ENox	70	
SO2	CSO2	ppm	4.59	Cout_SO2	ppm	0.23	ESO2	95	
HC(VOC)	CHC	ppm	60.00	Cout_HC	ppm	6.00	EHC	90	
CO	CCO	ppm	53.36	Cout_CO	ppm	53.36	Eco	0	
Particle	Cpart	mg/Nm3		Cout_part	mg/Nm3		Epart	%	
NH3 Stoichiometric Ratio(SR) to NO and SO2				SRNH3		1.5			
Labor Data									
Supervisor		MP/year	0.5	On the basis of 400000Nm3/hr					
Operator		MP/year	2.0	"					
Yard-crew Worker		MP/year	2.0	"					
Secretary		MP/year	0.5	"					
Unit Price Data									
Electrical Power		US\$/kWh	0.05	(Production Cost 0.02)					
Limestone		US\$/ton	16	14*1.2					
Lime		US\$/ton	72	60*1.2					
Gypsum		US\$/ton	24						
NH3		US\$/ton	180	(Retail : \$356 for 150lb)					
CH4		US\$/ton	73.46						
Ar		US\$/ton	100	(Retail : \$91 for 331ft3 at 2490psi)					
Water		US\$/ton	0.2						
Steam		US\$/ton	7						
Fertilizer		US\$/ton	90						
Waste Treatment(Sludge)		US\$/ton	10						
Personal									
Supervisor		US\$/year	52,942						
Operator		US\$/year	30,856						
Yard-crew Worker		US\$/year	20,998						
Secretary		US\$/year	24,583						
Economic Data									
Depreciation Period		Years	10						
Inflation Rate		%	5.0						
Real Interest Rate		%	5.0						
Nominal Interest Rate		%	10.3	[Calculated, $=(1+i)(1+e)-1$]					
Salvage Rate of Facilities		%	0.0						

Fig.1.3 b Design of a Pulse Corona System

Input Data from Pilot Test				Calculated Data for Commercial Plant Design			
Dust Collector (Module)				Dust Collector (Module)			
Type : Wire-Plate Electrostatic Precipitator				Collecting Area	Aesp	m ²	37
Efficiency	Eesp	%	95	Width	Wesp	m	0.90
Migration Velocity	VCmig	m/sec	0.125	Height	Hesp	m	1.15
Channel Width	Wespch	m	0.3	No. of Channel	Nespch		3
Gas Velocity	Vcesp	m/sec	1.5	Length	Lesp	m	11
No. of Module			2	Volume	VLesp	m ³	11
				Residence Time	TMesp	sec	4
				Electric Power		kW	4
Flue Gas System				Flue Gas System			
Inlet Temperature	Tscin	C	25	Flowrate	Qmod	Nm ³ /hr	10,200
Outlet Temperature	Tscout	C	25	Actual Flowrate	Qacmod	m ³ /hr	11,134
				NO _x Mass Flowrate	MFNO _x	kg/hr	0
				SO _x Mass Flowrate	MF _{SO_x}	kg/hr	0
				Electric Power		kW	16
Reagent Feed System				Reagent Feed System			
Limestone				Limestone Flowrate	QCaCO ₃	kg-mole	0.00
Ratio to SO ₂ Removed	SR _{CaCO₃}		1.15	Limestone Consump	MF _{CaCO₃}	kg/hr	0
Fixative Lime				Electric Power		kW	0
Wet Scrubbing Absorber Tower				Wet Scrubbing Absorber Tower (Module)			
Reactor Type : Vertical Countercurrent Spray				No. of Reactor Module	Nmod	ea	1
Max. Flowrate of Mod	Qxmod	Nm ³ /hr	2.0E+06	Flowrate/Module	Qmod	Nm ³ /hr	10,200
Gas Velocity	VCrc	m/sec	1.5	Actual Flowrate/Mod	Qacmod	m ³ /hr	11,134
				Diameter of Module		m	1.6
				Height of Module		m	1.5
				Volume of Module		m ³	3
				Water Consumption	MFscw	ton/hr	5
				Electric Power		kW	18
Reheat System				Reheat System (Module)			
Inlet Temperature	Trhin	C	25	Heat Flowrate	Q _h	MJ/hr	6,425
Outlet Temperature	Trhout	C	370	Steam Consumption	Qsteam	ton/hr	2.26
Flue Gas Specific Heat	Cpgas	kJ/kg	1.423				
Steam Inlet Temp.			233.3				
Steam Outlet Temp.			93.3				
Waste Handling System				Waste Handling System			
Recovery Rate	Erecov	%	-	Fly Ash		ton/hr	0.2
Ratio to Dry Sludge and Fly Ash			0.03	Waste Sludge		ton/hr	0.0
				Lime Consumption		ton/hr	0.0
				Total Waste		ton/hr	0.2
				Gypsum Recovery	Mfert	kg/hr	0.0
				Electric Power		kW	2
Power				Power			
				Total Power	Pin	MW	0.04
Selective Catalytic Reduction				Selective Catalytic Reduction (Module)			
NH ₃				NH ₃ Flowrate	Q _{NH₃}	Nm ³ /hr	0
Ratio to NO	SR _{NH₃}		1.20	NH ₃ Consumption	MF _{NH₃}	kg/hr	0
				Electric Power		kW	0

Fig.1.3c Design of a Pulse Corona System

Input Data from Pilot Test				Calculated Data for Commercial Plant Design			
Additional Gas				Gas			
Additional Gas I	SR _{NH3}		NH3	NOx Mass Flowrate	MF _{NOx}	kg/hr	0
Ratio to NO and SO2			1.50	SOx Mass Flowrate	MF _{SOx}	kg/hr	0
Additional Gas II	SR _{CH4}		CH4	NH3 Flowrate	Q _{NH3}	Nm3/hr	1
Ratio to NO and SO2			0.00	NH3 Consumption	MF _{NH3}	kg/hr	1
Additional Gas III	SR _{C2H4}		C2H4	CH4 Flowrate	Q _{CH4}	Nm3/hr	0
Ratio to NO and SO2			0.00	CH4 Consumption	MF _{CH4}	kg/hr	0
Water Spray Cooler				Water Spray Cooler			
Inlet Temperature	T _{scin}	C	25	Residence Time	TM _{sc}	sec	5.00
Outlet Temperture	T _{scout}	C	25	Cooler Volume	VL _{sc}	m3	15.46
Gas Velocity	VC _{sc}	m/sec	1.5	Inner Diameter	D _{scin}	m	2
Residence Time	TM _{sc}	sec	5	Length (Height)	L _{sc}	m	9
				Water Consumption	MF _{scw}	ton/hr	0
Reactor				Reactor			
Reactor Type :	Wire-Plate Type Reactor			No. of Reactor Module	N _{mod}	ea	1
Max. Flowrate of Mod	Q _{xmod}	Nm3/hr	500,000	Flowrate/Module	Q _{mod}	Nm3/hr	10,200
Flowrate/Channel	Q _{ch}	Nm3/hr	8,000	Actual Flowrate/Mod	Q _{acmod}	m3/hr	11,134
Volume of Channel	VL _{ch}	m3	20	No. of Channel/Mod	N _{ch}	ea	2
Channel Width	W _{ch}	m	0.2	Volume of Module	VL _{mod}	m3	40
Height of Module	H _{mod}	m	10	Width of Module	W _{mod}	m	0.40
				Length of Module	L _{mod}	m	10.00
				Area of Electrode/Mod	A _{elec}	m2	200
				Gas Velocity	VC _{rc}	m/sec	0.77
				Residence Time	TM _{res}	sec	12.93
Pulse Generator (Unit)				Power			
Power Supply Type :	Rotary Spark-Gap			Total Corona Power	P _{co}	MW	0.02
Max. Peak Voltage	V _{max}	kV	120	Total Input Power	P _{in}	MW	0.03
Power of Unit	P _{umax}	MW	0.2	No. of Supply Unit	N _{psu}	ea	1
Efficiency(In->Gas)	E _{ps}	%	60				
Energy Yield				Fertilizer			
for NOx (from Data)	Y _{NOx}	g/kWh	20.00	Ideal Total Production	Midfert	kg/hr	1
for SO2 (from Data)	Y _{SO2}	g/kWh	1.0E+06	Recovery	Mfert	kg/hr	1
(Spec. Energy Density)	EN _{den}	J/L	6.08				
(Power Density)	P _{den}	Wh/m3	1.69				
Dust Collector (Module)				Dust Collector (Module)			
Type :	Wire-Plate Electrostatic Precipitator			Collecting Area	A _{esp}	m2	74
Efficiency	E _{esp}	%	95	Width	W _{esp}	m	0.40
Migration Velocity	VC _{mig}	m/sec	0.125	Height	H _{esp}	m	10.00
Channel Width	W _{espch}	m	0.3	No. of Channel	N _{espch}		1
Fertilizer Recovery	E _{fert}	%	50	Length	L _{esp}	m	7.41
				Volume	VL _{esp}	m3	30
				Residence Time	TM _{esp}	sec	9.59
				Gas Velocity	VC _{esp}	m/sec	0.77

Fig.1.3d Design of Electron Beam Systems

Input Data				Calculated Data			
Additional Gas				Gas			
Additional Gas I	MR _{NH3}		NH3	NOx Mass Flowrate	MF _{NOx}	kg/hr	0
Ratio to NO and SO2			1.50	SOx Mass Flowrate	MF _{SOx}	kg/hr	0
Additional Gas II	MR _{CH4}		CH4	NH3 Flowrate	Q _{NH3}	Nm3/hr	1
Ratio to NO and SO2			0.00	NH3 Consumption	MF _{NH3}	kg/hr	1
				CH4 Flowrate	Q _{CH4}	Nm3/hr	0.00
				CH4 Consumption	MF _{CH4}	kg/hr	0.00
Water Spray Cooler				Water Spray Cooler			
Inlet Temperature	Tscin	C	25	Cooler Volume	VLsc	m3	15.46
Outlet Temperature	Tscout	C	25	Inner Diameter	Dscin	m	2
Gas Velocity	VCsc	m/sec	1.5	Length (Height)	Lsc	m	8
Residence Time	TMsc	sec	5	Water Consumption	MFscw	ton/hr	0
Reactor				Reactor			
Reactor Type : Horizontal Square				No. of Reactor Module	Nmod	ea	1
Max. Flowrate of Mod	Qxmod	Nm3/hr	400,000	Flowrate/Module	Qmod	Nm3/hr	10,200
Flowrate/Channel	Qch	Nm3/hr	200,000	Actual Flowrate/Mod	Qacmod	m3/hr	11,134
Volume of Channel	VLch	m3	200	No. of Channel/Mod	Nch	ea	1
Channel Width	Wch	m	5	Volume of Module	VLmod	m3	200
Height of Module	Hmod	m	5	Width of Module	Wmod	m	5.00
Shield Thickness	Wshield	m	1	Length of Module	Lmod	m	8.00
Shield Space	Lshield	m	5	Gas Velocity	VCrc	m/sec	0.12
				Residence Time	TMres	sec	64.67
				Shield Surface Area	Ashield	m2	1,530
E-Beam Gun				E-Beam Gun			
Voltage of Gun	Vgun	kV	1000	EB Power/Module	Pmod	MW	0.02
Max. Current of Gun	Igun	mA	1500	Input Power/Module	Pmodin	MW	0.02
(Max. Power of Gun)	Pxgun	kW	1500	No. of EB Guns/Ch	Ngunch	ea	1
Efficiency (Input->Gas)	Egun	%	80	Gun Power	Pgun	kW	200
Min. Power of Gun	Pmngun	kW	200	Total No. of EB Guns	Ngun	ea	1
				Total EB Power	Peb	MW	0.02
				Total Input Power	Pin	MW	0.20
Energy Yield				Fertilizer			
for NOx (from Data)	Y _{NOx}	g/kWh	19.1	Ideal Total Production	Midfert	kg/hr	1
for SO2 (from Data)	Y _{SO2}	g/kWh	1.0E+06	Recovery	Mfert	kg/hr	1
(Dosage)	ITeb	kGy	(5.0)				
Dust Collector (Module)				Dust Collector (Module)			
Type : Wire-Plate Electrostatic Precipitator				Collecting Area	Aesp	m2	74
Efficiency	Eesp	%	95	Width	Wesp1	m	0.40
Migration Velocity	VCmig	m/sec	0.125	Height	Hesp	m	10.00
Channel Width	Wespch	m	0.3	No. of Channel	Nespch		2
Fertilizer Recovery	Efert	%	50	Revised Width	Wesp	m	0.60
				Length	Lesp	m	3.71
				Volume	VLesp	m3	22
				Residence Time	TMesp	sec	7.19
				Gas Velocity	VCesp	m/sec	0.77

Fig.13e Design of Corona Radical Shower System

Input Data				Calculated Data			
Additional Gas and Nozzle				Gas			
Additional Gas I Ratio to NO + 2*SO2	MR _{NH3}		NH3 1.50	NOx Mass Flowrate	MF _{NOx}	kg/hr	0
Additional Gas II Ratio to NO + 2*SO2	MR _{CH4}		CH4 0.00	SOx Mass Flowrate	MF _{SOx}	kg/hr	0
				NH3 Flowrate	Q _{NH3}	Nm3/hr	1
				NH3 Consumption	MF _{NH3}	kg/hr	1
				CH4 Flowrate	Q _{CH4}	Nm3/hr	0.00
				CH4 Consumption	MF _{CH4}	kg/hr	0.00
Water Spray Cooler				Water Spray Cooler			
Inlet Temperature	T _{scin}	C	25	Cooler Volume	VL _{sc}	m3	15.46
Outlet Temperature	T _{scout}	C	25	Inner Diameter	D _{scin}	m	2
Gas Velocity	VC _{sc}	m/sec	1.5	Length (Height)	L _{sc}	m	8
Residence Time	TM _{sc}	sec	5	Water Consumption	MF _{scw}	ton/hr	0
Reactor				Reactor			
Reactor Type :	Tube-Plate Type Reactor			No. of Reactor Module	N _{mod}	ea	1
Max. Flowrate of Mod	Q _{xmod}	Nm3/hr	500,000	Flowrate/Module	Q _{mod}	Nm3/hr	10,200
Flowrate/Channel	Q _{ch}	Nm3/hr	8,000	Actual Flowrate/Mod	Q _{acmod}	m3/hr	11,134
Volume of Channel	VL _{ch}	m3	25	No. of Channel/Mod	N _{ch}	ea	2
Channel Width	W _{ch}	m	0.2	Volume of Module	VL _{mod}	m3	50
Height of Module	H _{mod}	m	10	Width of Module	W _{mod}	m	0.40
				Length of Module	L _{mod}	m	12.50
				Area of Electrode/Mod	A _{elec}	m2	250
				Gas Velocity	VC _{rc}	m/sec	0.77
				Residence Time	TM _{res}	sec	16.17
Power Supply (Unit)				Power			
Power Supply Type :	DC High Voltage			Total Corona Power	P _{co}	MW	0.02
Max. Voltage	V _{max}	kV	120	Total Input Power	P _{in}	MW	0.03
Max. Power of Unit	P _{umax}	MW	10	No. of Supply Unit	N _{psu}	ea	1
Efficiency(In->Gas)	E _{ps}	%	60	Power of Unit	P _{unit}	MW	0.1
Energy Yield				Fertilizer			
for NOx (from Data)	Y _{NOx}	g/kWh	17	Ideal Total Production	Midfert	kg/hr	1
for SO2 (from Data)	Y _{SO2}	g/kWh	1.0E+06	Recovery	Mfert	kg/hr	1
(Spec. Energy Density)	EN _{den}	J/L	7.15				
(Power Density)	P _{den}	Wh/m3	1.985				
Dust Collector (Module)				Dust Collector (Module)			
Type :	Wire-Plate Electrostatic Precipitator			Collecting Area	A _{esp}	m2	74
Efficiency	E _{esp}	%	95	Width	W _{esp}	m	0.40
Migration Velocity	VC _{mig}	m/sec	0.125	Height	H _{esp}	m	10.00
Channel Width	W _{espch}	m	0.3	No. of Channel	N _{espch}		1
Fertilizer Recovery	E _{fert}	%	50	Length	L _{esp}	m	7.41
				Volume	VL _{esp}	m3	30
				Residence Time	TM _{esp}	sec	9.59
				Gas Velocity	VC _{esp}	m/sec	0.77

Fig. 1.3f

Gas Flow Rate 1.00E+05 Nm³/h (5.89E+04 SCFM)

	Pulse	Corona	Corona	Shower	Electron	Beam	Wet Scrubb	+ SCR	ESP	+SCR
Capital Recovery	345		410		718		36		104	
Labor & Maintenance	218		246		377		273		273	
Electric Power	99		116		77		123		83	
Chemicals & Utilities	6		6		6		1,291		1,192	
Total Annual Cost		664		774		1,176		1,723		1,651
Fertilizer Recovery		4		4		4		0		0

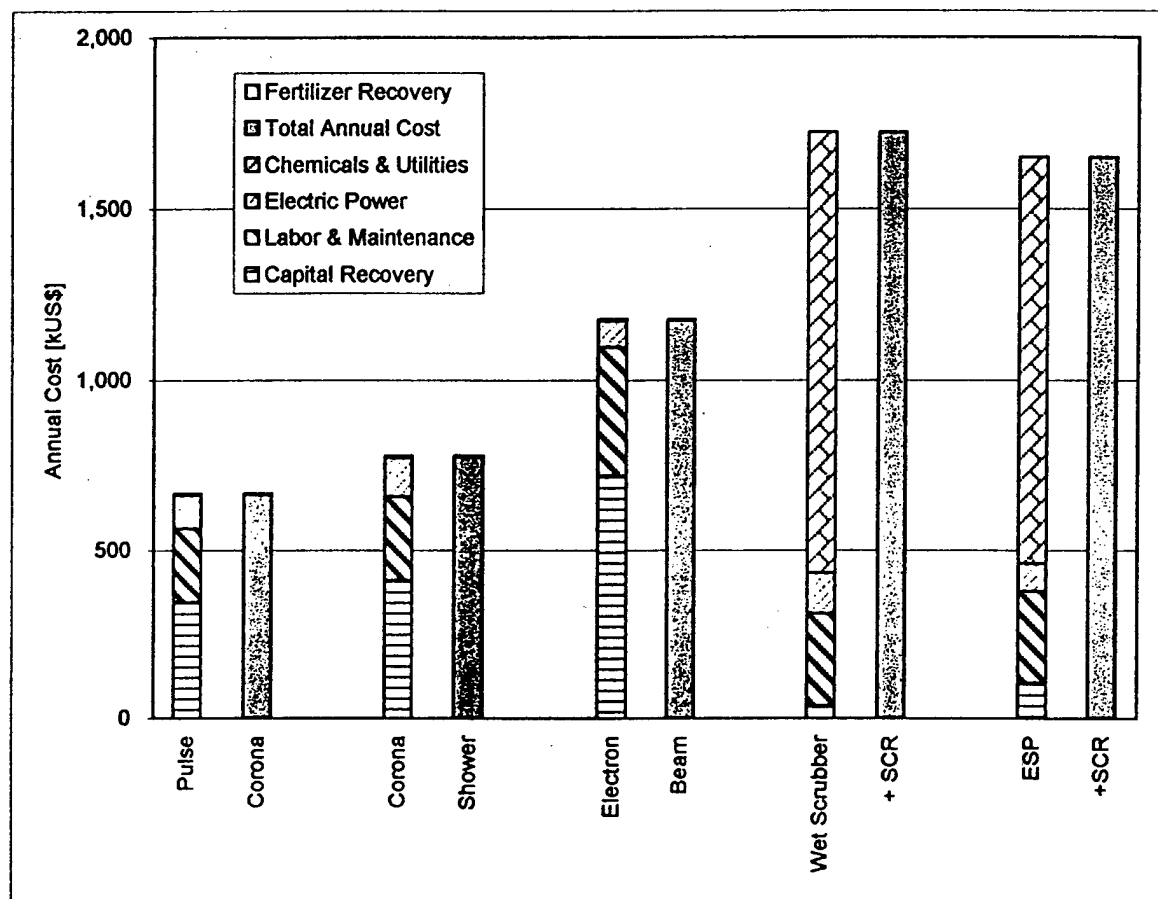


Fig.1-3 g Comparison of Important Factors and Results

Important Factors and Results	Unit	Pulse Corona	Corona Radical Shower	Electron Beam	Wet Scrubber + SCR	SCR + ESP
Performance						
Additional Gas						
NH ₃ Molar Ratio		1.50	1.50	1.50	1.20	1.20
NH ₃ Consumption	kg/hr	5	5	5	3	4
Reactor						
No. of Reactor Module	ea	1	1	1	1	2
No. of Channel per Module	ea	13	13	1	0	10
Volume of Reactor Module	m ³	260	325	200	57	109
Area of Cathode Plates	m ²	1,300	1,625	-	-	-
Gas Velocity in Reactor	m/sec	1.17	1.17	1.21	1.50	1.50
Residence Time in Reactor	sec	8.57	10.72	6.60	0.00	3.59
Power Supply or EB Gun						
Voltage	kV	120	120	1,000	0	0
Max Current	mA	-	-	1,500	0	0
Power	MW	0.20	0.40	0.22	0.17	0.00
Efficiency (Input -> Gas)	%	60	60	80	95	0
No. of P/S or EB Gun	ea	2	1	1	0	0
Total Input Power	MW	0.28	0.33	0.22	0.35	0.24
Energy Yield						
for NOx	g/kWh	20.0	17.0	19.1	0.0	0.0
for SOx	g/kWh	1.0E+06	1.0E+06	1.0E+06	0.0	0.0
Total Capital Investment						
	kUS\$	2,095	2,491	4,367	221	630
	US\$/(kNm ³ /h)	20,948	24,912	43,668	2,211	6,298
Spray Cooler	kUS\$	0	0	0	0	0
Reactor	kUS\$	602	924	188	32	32
Power Supply or EB Gun	kUS\$	326	241	1,094	31	0
Shield Construction	kUS\$	0	0	1,102	0	0
Dust Collector	kUS\$	268	268	268	0	299
Instrumentation	kUS\$	133	149	120	2	3
Others	kUS\$	67	79	139	52	52
Direct Cost	kUS\$	1,397	1,661	2,911	147	420
Indirect Cost	kUS\$	698	830	1,456	74	210
Direct Annual Cost	kUS\$	323	368	461	1,687	1,547
Electric Power	kUS\$	99	116	77	123	83
Chemicals & Utilities	kUS\$	6	6	6	1,291	1,192
Labor	kUS\$	71	71	71	75	75
Maintenance	kUS\$	147	174	306	198	198
Capital Recovery/Depreciation	kUS\$	345	410	718	36	104
Fertilizer Recovery	kUS\$	4	4	4	0	0
Total Annual Cost	kUS\$	664	774	1,176	1,723	1,651
Levelized Annual Cost	kUS\$	750	873	1,299	2,179	2,069

Gas Flow Rate 1.00E+05 Nm³/h
(5.89E+04 SCFM)

Fig. 1.3 h

Gas Flow Rate 1.00E+06 Nm³/h (5.89E+05 SCFM)

	Pulse	Corona	Corona	Shower	Electron Beam	Wet Scrubb	+ SCR	ESP	+SCR
Capital Recovery	2,089		2,321		3,954	1,489		1,496	
Labor & Maintenance	1,114		1,213		1,908	2,731		2,731	
Electric Power	986		1,159		776	1,225		826	
Chemicals & Utilities	65		65		65	12,910		11,917	
Total Annual Cost		4,217		4,722	6,666	18,356		16,970	
Fertilizer Recovery		36		36	36	0		0	

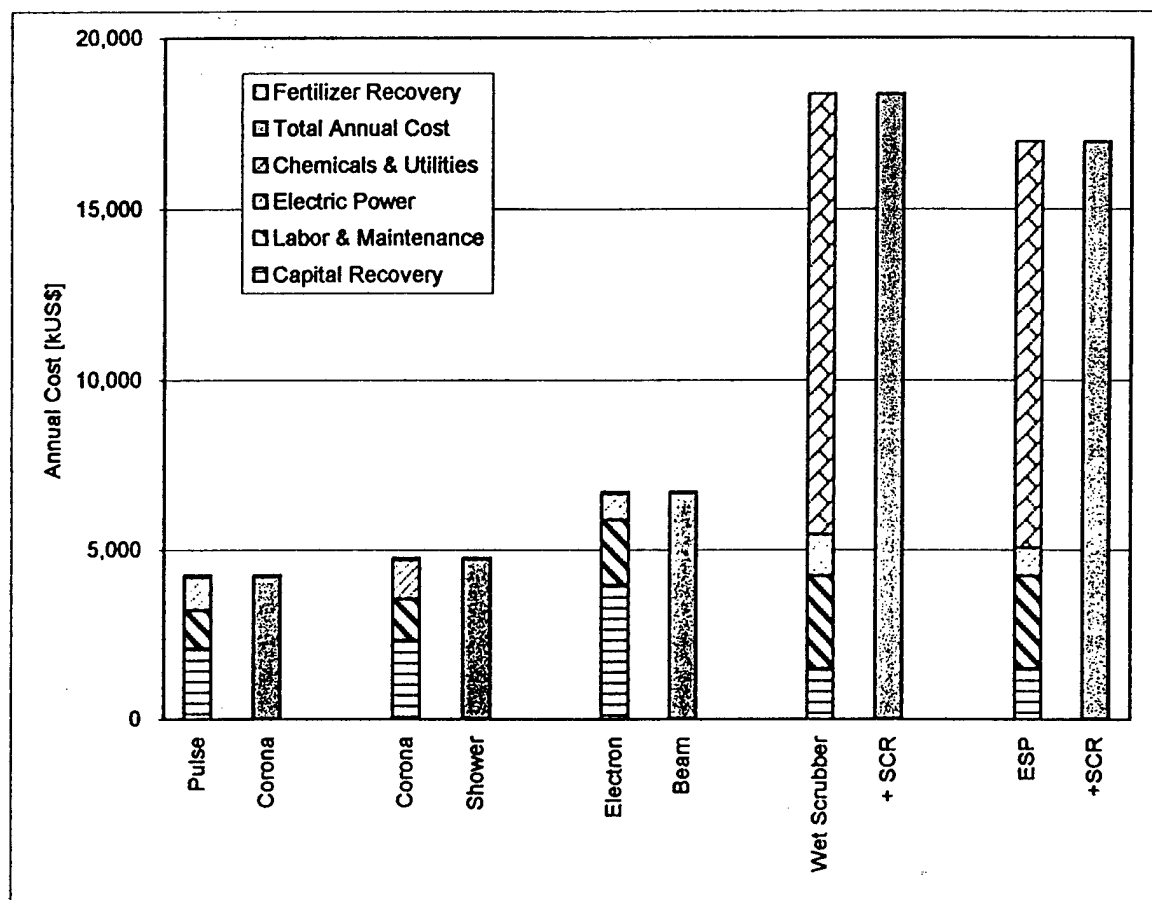


Fig. 1.3 i Comparison of Important Factors and Results

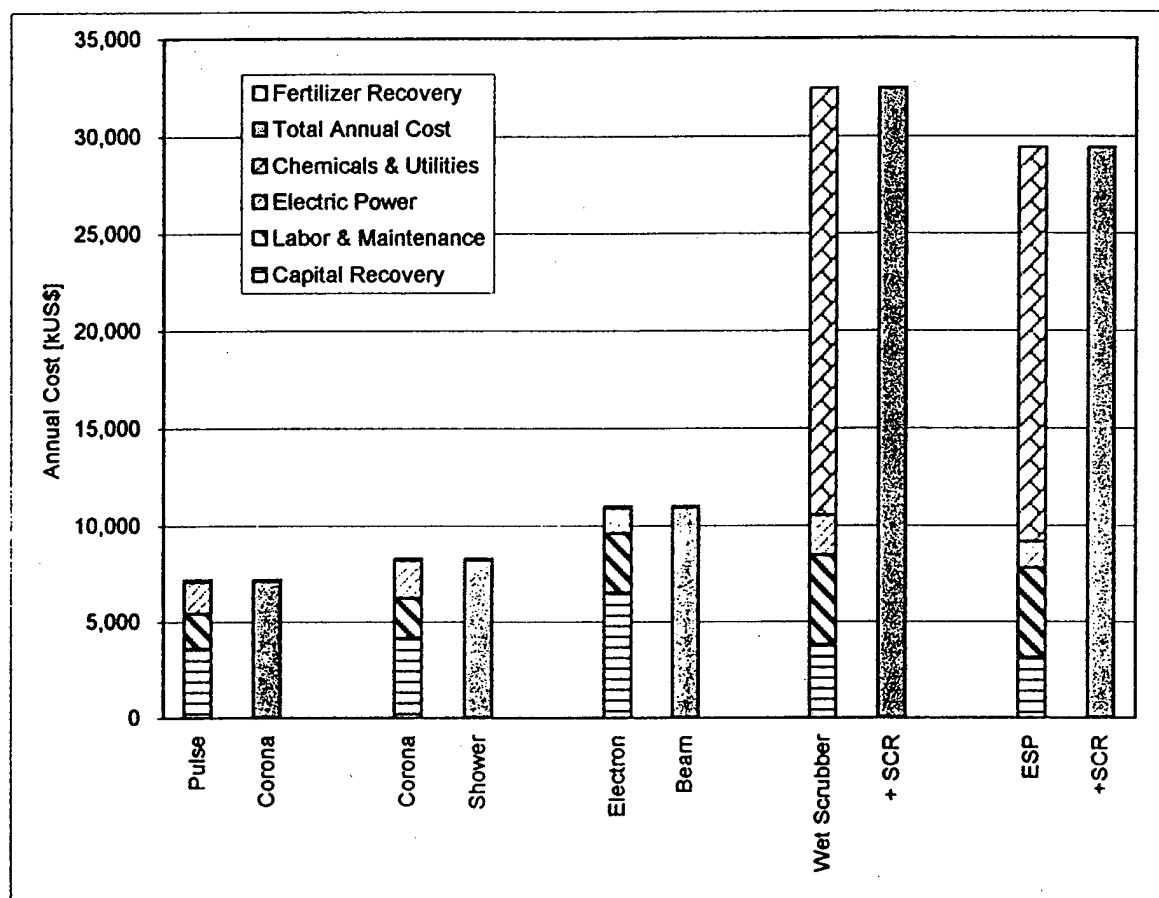
Important Factors and Results	Unit	Pulse Corona	Corona Radical Shower	Electron Beam	Wet Scrubber + SCR	SCR + ESP
Performance						
Additional Gas						
NH ₃ Molar Ratio		1.50	1.50	1.50	1.20	1.20
NH ₃ Consumption	kg/hr	51	51	51	33	36
Reactor						
No. of Reactor Module	ea	2	2	3	1	2
No. of Channel per Module	ea	63	63	2	0	33
Volume of Reactor Module	m ³	1,260	1,575	400	2,121	1,090
Area of Cathode Plates	m ²	6,300	7,875	-	-	-
Gas Velocity in Reactor	m/sec	1.20	1.20	2.02	1.50	1.50
Residence Time in Reactor	sec	8.31	10.39	3.96	0.00	3.59
Power Supply or EB Gun						
Voltage	KV	120	120	1,000	0	0
Max Current	mA	-	-	1,500	0	0
Power	MW	0.20	1.70	0.37	1.74	0.00
Efficiency (Input -> Gas)	%	60	60	80	95	0
No. of P/S or EB Gun	ea	15	2	6	0	0
Total Input Power	MW	2.81	3.31	2.21	3.50	2.36
Energy Yield						
for NOx	g/kWh	20.0	17.0	19.1	0.0	0.0
for SOx	g/kWh	1.0E+06	1.0E+06	1.0E+06	0.0	0.0
Total Capital Investment						
	kUS\$	12,697	14,111	24,038	9,051	9,093
	US\$/(kNm ³ /h)	12,697	14,111	24,038	9,051	9,093
Spray Cooler	kUS\$	0	0	0	0	0
Reactor	kUS\$	3,245	4,977	884	1,624	1,624
Power Supply or EB Gun	kUS\$	2,448	1,536	8,397	1,570	0
Shield Construction	kUS\$	0	0	2,523	0	0
Dust Collector	kUS\$	2,082	2,082	2,219	0	2,082
Instrumentation	kUS\$	287	364	238	83	166
Others	kUS\$	403	448	763	520	520
Direct Cost	kUS\$	8,465	9,407	16,025	6,034	6,062
Indirect Cost	kUS\$	4,232	4,704	8,013	3,017	3,031
Direct Annual Cost	kUS\$	2,164	2,437	2,749	16,867	15,474
Electric Power	kUS\$	986	1,159	776	1,225	826
Chemicals & Utilities	kUS\$	65	65	65	12,910	11,917
Labor	kUS\$	225	225	225	754	754
Maintenance	kUS\$	889	988	1,683	1,977	1,977
Capital Recovery/Depreciation	kUS\$	2,089	2,321	3,954	1,489	1,496
Fertilizer Recovery	kUS\$	36	36	36	0	0
Total Annual Cost	kUS\$	4,217	4,722	6,666	18,356	16,970
Levelized Annual Cost	kUS\$	4,792	5,371	7,399	22,913	21,151

Gas Flow Rate 1.00E+06 Nm³/h
(5.89E+05 SCFM)

Fig. 1.3j

Gas Flow Rate 1.70E+06 Nm³/h (1.00E+06 SCFM)

	Pulse	Corona	Corona	Shower	Electron Beam	Wet Scrubb	+ SCR	ESP	+SCR
Capital Recovery	3,594		4,151		6,504	3,802		3,123	
Labor & Maintenance	1,823		2,060		3,061	4,641		4,641	
Electric Power	1,674		1,970		1,318	2,082		1,403	
Chemicals & Utilities	110		110		110	21,935		20,247	
Total Annual Cost		7,139		8,230	10,931		32,459		29,414
Fertilizer Recovery		62		62	62		0		0



However the dc power supply was not the main part of CS process capital cost since it is much less inexpensive than an electron beam gun and pulsed generator. The most outstanding parameter which strongly affects both the capital cost and operating cost is energy yield. Low energy yield require less power supply capacity and less electric power consumed. This is another reason corona shower process has the low total annual cost including capital recovery. The total annual cost of pulsed corona system is almost the same with electron beam and corona shower system. All systems have slightly lower than the half of the total annual cost of conventional combined system.

Although only 50% of producible fertilizer is assumed to be recovered, the recovery credit can be high enough not to be negligible. If electrostatic precipitators are equipped at the both sides of each non-thermal system, good quality fertilizer of ammonia sulfate nitrate could be obtained. For the conventional system, gypsum could be recovered can if it is not significant amount.

All of the non-thermal plasma systems show 50 to 60% lower costs by comparison with conventional wet-scrubber/SCR or SCR/ESP systems for the present range of gas flow rates (10^5 to 10^7 Nm³/h).

1.5 CONCLUDING REMARKS

The computer code SUENTP-J was developed to predict scale-up and economic evaluations of several eligible non-thermal plasma processes for Jet Engine Test Cell exhaust gas pollution controls. This code was written using a spread sheet (MS Excel) with Visual Basic for application and comprise a data input procedure, scale-up (design) procedure, economic calculation procedure, and output procedure.

This code has obtained the parametric economic evaluation of three non-thermal systems and has shown competitive with the conventional system. The result of the evaluation also shows that the

NTP system energy yield of NO_x and SO_x removal to be the most important parameter to affect the capital cost as well as the operating cost. Hence, any possible pilot study of non-thermal emission control systems should be clearly designed to present the value of the energy yield as well as De- NO_x and De- SO_x efficiency. In order to estimate more accurate non-thermal plasma system costs for JETC and CMTC conditions, much larger pilot plant tests, up to 200 to 1000 Nm^3/h , are required.

REFERENCES

Bartoszek, F.E, Vasquez, E.R, He, W. and Chang, J.S., 1998, Removal of NO_x from the Flue Gas by Reburning with Plasma Activated Natural Gas: Review and Economics, *Combust Sci. Tech.* Vol. 28, pp.169-198.

Civitano, L., 1993, Industrial Application of Pulsed Corona Processing to Flue Gas, in *Non-thermal Plasma Techniques for Pollution Control*, ed. Penetrante, B.M. and Schultheis, S.E., NATO ASI Series G, Vol. 34, Part B, pp. 103-130, Springer-Verlag, Berlin, Heidelberg.

Ebara Co., 1998, Commercial Catalogue CC3402J.

EPRI, 1983, Economical Evaluation of FGD Systems, EPRI Report CS-3342, Volume 1-5, Dec.

EPRI, 1991, Technical Assessment Guide, EPRI Report TR-100281s Volume 3, Dec.

Frank, N.W., and Hirano, S., 1994, The Use of Electrons for Removal of SO_2 and NO_x From Flue Gases, *Global '90*.

Japanese Mechanical Industry Association and Energy Engineering Institute (JMIA-EEI), 1991, Technology Investigation Report of New Dry De- SO_x and Technologies for Gas of Coal-Fired Power Plant Boiler Using Pulsed Corona Plasma Chemical Process (in Japanese).

Candor, M., Ehrlich, E.M. and Riche, M.F., 1996, Statistical Abstract of the United States, 1996, The National Data Bank.

Kim, S.J., and Chang, J.S., 1998, SUENTP Code Simulations of Scale-Up and Economic Evaluation of Non-Thermal Plasma Technology for Exhaust Gas Emission of Coal Fixed Power Plant, Proc. ICESP-7, vol. 1, pp.168-176.

Haythornthwaite, S.M., Durham, M.D., Rugg, D. and Wander, J.D., 1997, Application of Pulse-Corona Induced Plasma to Jet Engine Test Cells, Presented at Air & Waste Management Association 90th Ann. Meeting, Toronto, June 1997.

Li, Z.S., Aoki, S. and Chang, J.S., 1997, Non-Thermal Plasma Commercial Plants and Pilot Studies in China, *Proc. ISNPT'97*, J.S. Chang and J.L. Ferreira, Eds., Catholic University of Brasilia Press, Brazil, pp. 7-8.

Matsuoka, M., Kim, S.J., Looy, P.C. and Chang, J.S., 1997, Economic, Evaluation and Development of Scaling Algorithms for Non-Thermal Plasma Reactors for Control of NO_x . Released during Army and Related U.S., Department of Defence Operations, Contract Report No. DAAL01-97-p-1250.

Tokunaga, O., Namba, H., Tanaka, M., Kokura, Y., Doi, S., Aoki, S. and Izutsu, M., 1995, Development of Electron Beam Flue Gas Control Systems, Environmental Research (Japan), No. 99, pp. 17-23.

Vatavuk, W.M., 1990, Estimating Costs of Air Pollution Control, Lewis Publishers, Michigan.

PART 2.

ACID GAS REMOVAL CHARACTERISTICS OF CORONA RADICAL SHOWER-CATALYST HYBRID SYSTEM FOR TREATMENT OF STATIONARY ENGINE FLUE GAS

ABSTRACT

Acid gas removal experiments are carried out in a large bench scale corona radical shower reactor-catalyst hybrid system. A simulated stationary engine flue gas is air mixed with NO, SO₂ and CH₄. Optimizations for acid gas removal rates have been conducted in terms of the ammonia or methane to acid gas molar ratio, the applied voltage and the additional gas velocity. Both the removal efficiencies of NO and SO₂ increase with increasing applied voltage and decreasing initial NO concentration. It is also shown that high concentrations of CH₄ in flue gas have a negative effect on NO removal, where part of the NO is converted only to NO₂ but not to ammonium nitrate aerosol particles. The effect of catalytic reactions is larger with NH₃ injections but not significant for CH₄ injections for NO_x removal. However, SO₂ removal significantly enhanced by catalysts.

2.1 INTRODUCTION

NO_x and SO_x are air pollutants of concern and the major cause of acid rain. Many NO_x and SO_x conversion techniques such as wet scrubber, selective catalytic reactor, sorbent injection, low NO_x burner, etc., have been used. More recently, non-thermal plasma techniques have been used in commercial plants, however, the energy efficiency of the non-thermal plasma reactors have not yet been optimized. For example, the electron beam, barrier discharge and pulsed corona reactors, i.e.

direct plasma treatments of flue gases, may lose input energy to activate unwanted components of flue gases such as CO_2 , N_2 , etc. Hence, the corona discharge radical injection techniques have been developed. On the other hand, the treatment of an engine combustion flue gas by non-thermal plasmas have been investigated by many researchers [1-5]. In this work, an experimental investigation has been conducted to remove NO_x and SO_2 from stationary engine flue gases.

2.2 EXPERIMENTAL APPARATUS

The schematics of the experimental test loop and corona radical shower electrode are shown in Fig. 2.1. In stationary engine flue gas treatments, the combustion flue gas was normally diluted by air for cooling down to room temperature. In the present simulated flue gas test, the concentration ratio between NO and SO_2 or CH_4 are fixed at 0.128 or 1.667, respectively, and then NO initial concentration was varied from 30 to 100 ppm. NO , NO_2 and SO_2 concentrations were measured by a Green Line gas analyzer and the trace by-products are determined by Fourier Transform Infra-Red spectroscopy (FTIR). The aerosol particles generated by the acid gases and ammonia/methane related plasma processes were collected by the electrostatic precipitator operated at -19 kV dc downstream of the reactor. The size of the reactor is (10×30×100 cm) and three radical injectors are placed in series as shown in Fig. 2.1. The corona radical shower electrode used was a 6 mm o.d. tube equipped with 28 hollow electrodes (1.2 mm i.d./1.5 mm o.d.) as shown in Fig. 2.1b. Additional gas consisting of an air- NH_3 mixture was injected from these hollow electrodes to the reactor via the corona discharge generated by a positive dc high voltage at the edge of the hollow electrodes. Catalyst is placed 20 cm downstream of corona shower reactor and electrically heated by heating tapes.

2.3 EXPERIMENTAL RESULTS WITHOUT CATALYSTS

NO, NO_x and SO₂ removal rates as a function of applied voltage, ammonia-to-acid gas molecule ratio MR, additional gas superficial velocity and NO initial concentration are shown in Figs. 2.2, 2.3, 2.4 and 2.5, respectively, where the bar for each experimental point shows the minimum and maximum values observed during the transient tests. NO, NO_x and SO₂ removal rates increase with increasing applied voltage and decreasing NO initial concentration in flue gases as shown in Figs. 2.2 and 2.5, respectively, as expected from radical chemistry and heterogeneous reactions [5]. However, the acid gas removal rate has an optimum value in terms of MR and corona radical shower system additional gas velocity as shown in Figs. 2.3 and 2.4, respectively, where the NO and NO_x removal rate is maximum near molecule ratio between 1 to 1.5 and additional gas velocity near 8 m/s. Based on an analysis of Ohkubo et al [6], the effect of additional gas velocity can be explained by the better mixing of ammonia radicals to react with acid gases in lower velocity regions, where the mixing effect increases with increasing additional gas flow rates. For higher additional gas velocities, the ammonia radicals ejected from the hollow electrode may have shorter residence times in the reactor and only generate narrow flow channels to reduce reactions. Hence, the optimum additional gas flow velocity exists for the flue gas flow rate 6 Nm³/h or reactor superficial velocity of 0.056 m/s.

Based on corona discharge gas phase and heterogeneous reactions with ammonia [5], the SO₂ removal rate increases with increasing MR as shown in Fig. 2.3. However, if we examined discharge by-products, ammonia and methane relative concentrations (\propto absorbance of IR) as shown in Fig. 2.6, CH₄ and N₂O concentrations are minimized at molecule ratio near 1 to 1.5 where NH₃, H₂O and ϕ -CHO were determined by the IR absorptions at the wave length 964, 3017, 1304, 1551 and 1709 cm⁻¹ in Fig. 2.6. For the molecule ratio below 1, NO and NO_x are removed by a reduction

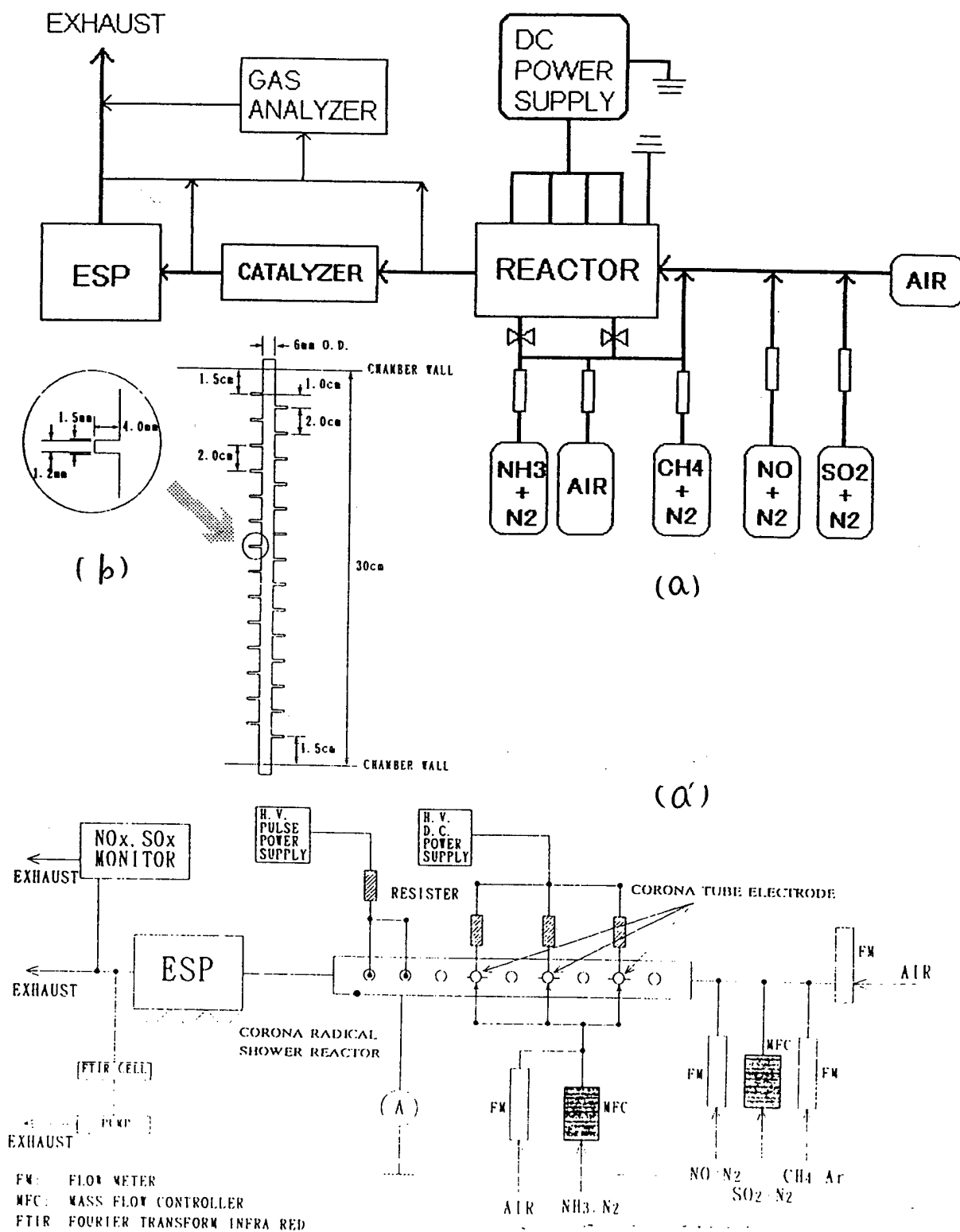
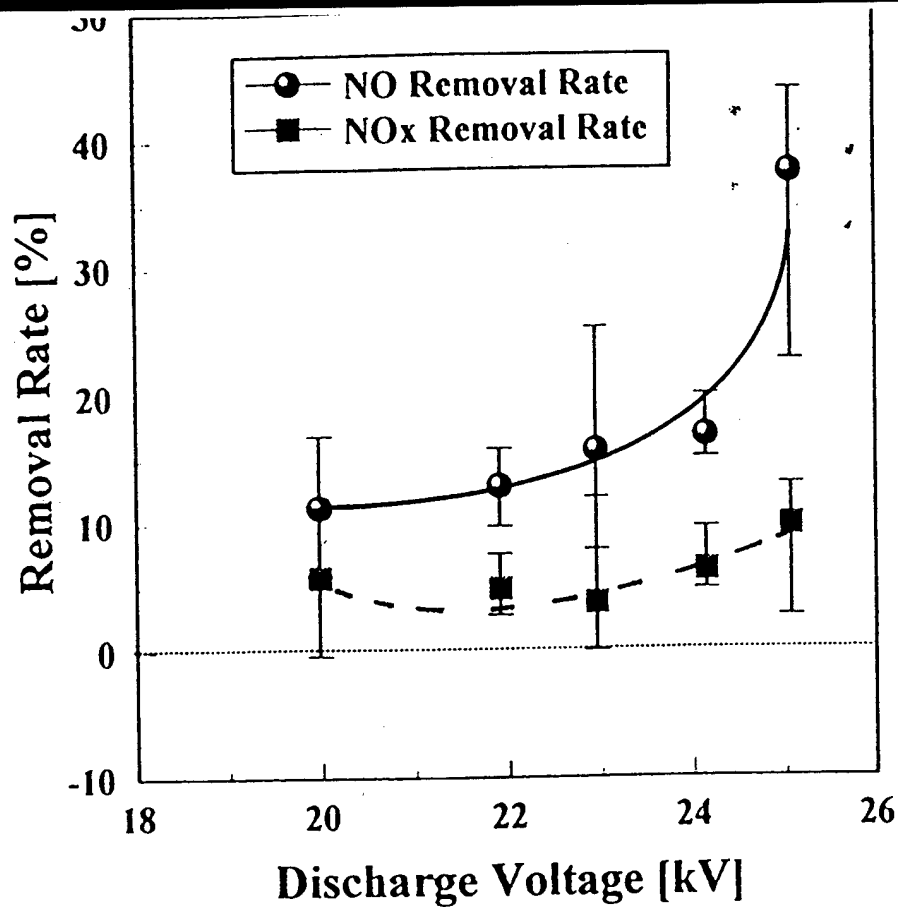
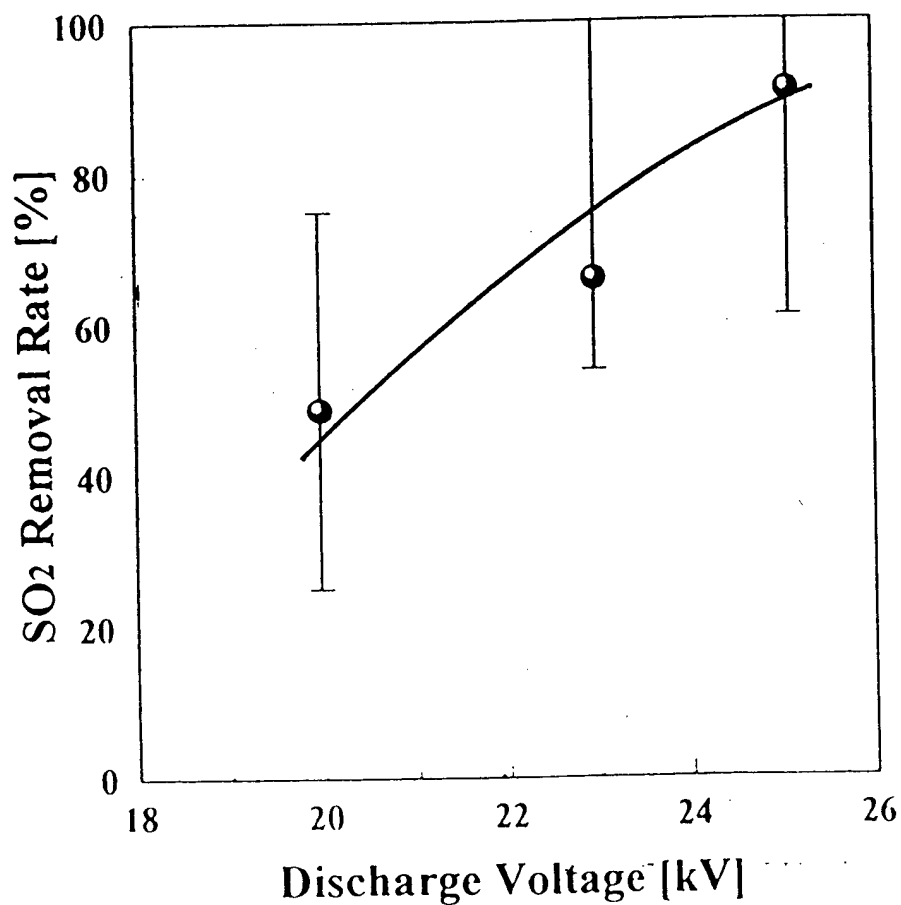


Fig. 2.1 Schematics of experimental flow loop (a) and corona radical shower electrode (b).

(a)



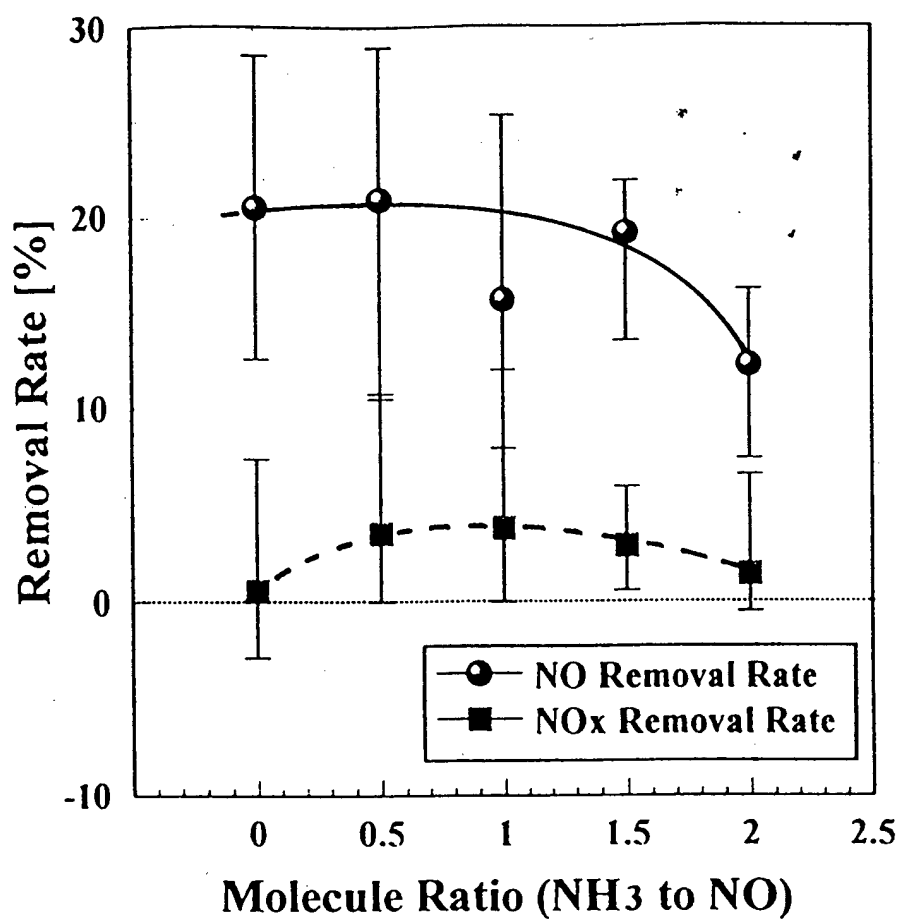
(b)



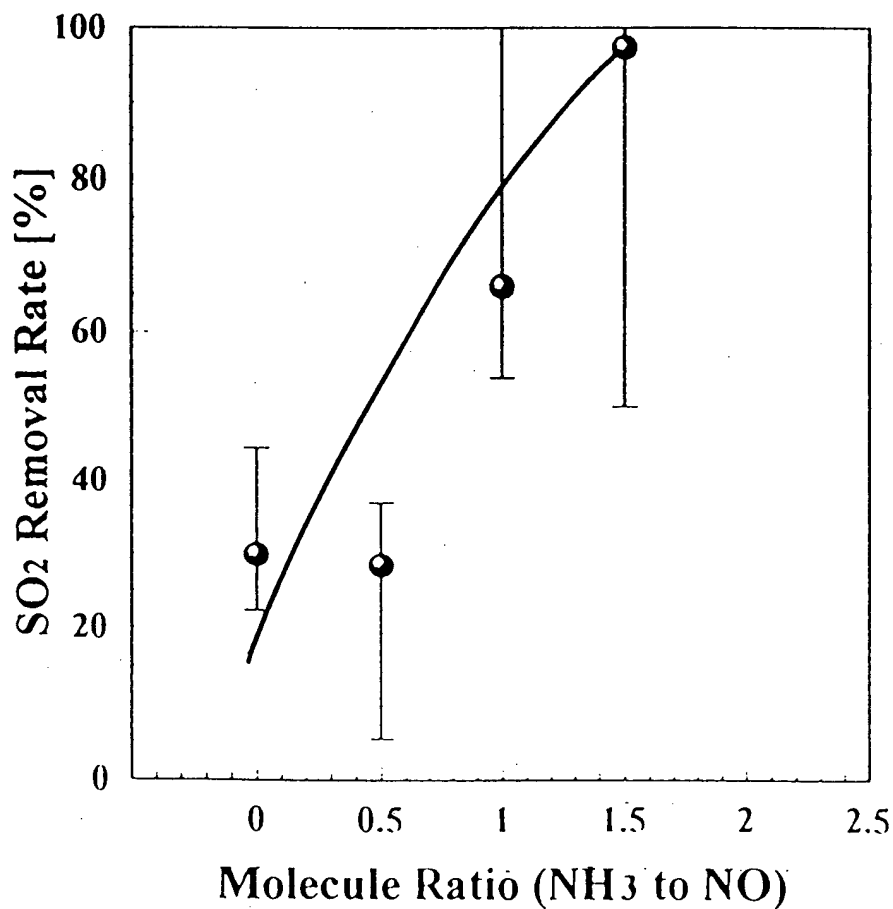
($Q_{\text{air}}=100\text{L/min}$, $w_d=5\text{m/sec}$, $M.R.=1$, Initial $\text{NO}=100\text{ppm}$)

Fig. 2.2 Acid gas removal rate as a function of corona shower system applied voltage V , where bar in the each experimental points indicated minimum and maximum values. a) NO and NO_x and b) SO₂.

(a)



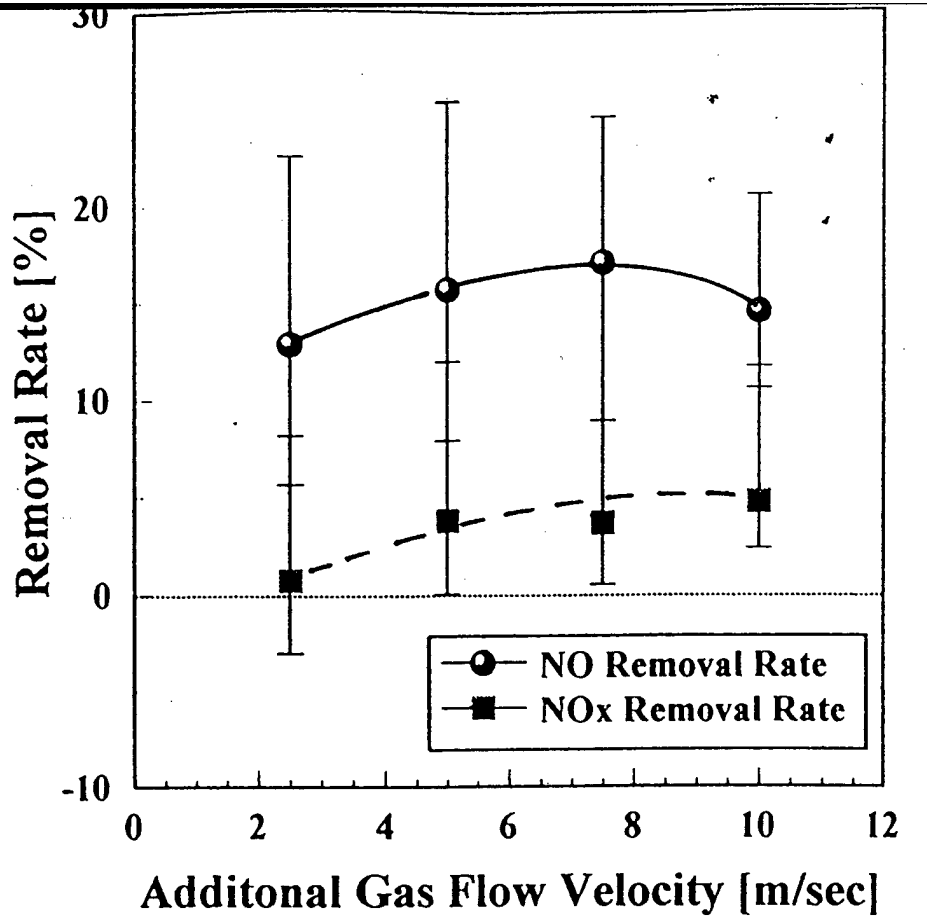
(b)



($Q_{\text{main}}=100\text{L/min}$, $v_{\text{add}}=5\text{m/sec}$, $V=23\text{kV}$, Initial NO=100ppm)

Fig. 2.3 Acid gas removal rate as a function of ammonia to acid gas molecule ratio MR. a) NO and NO_x and b) SO₂.

(a)



($Q_{\text{main}}=100\text{L/min}$, $M.R.=1$, $V=23\text{kV}$, Initial $\text{NO}=100\text{ppm}$)

(b)

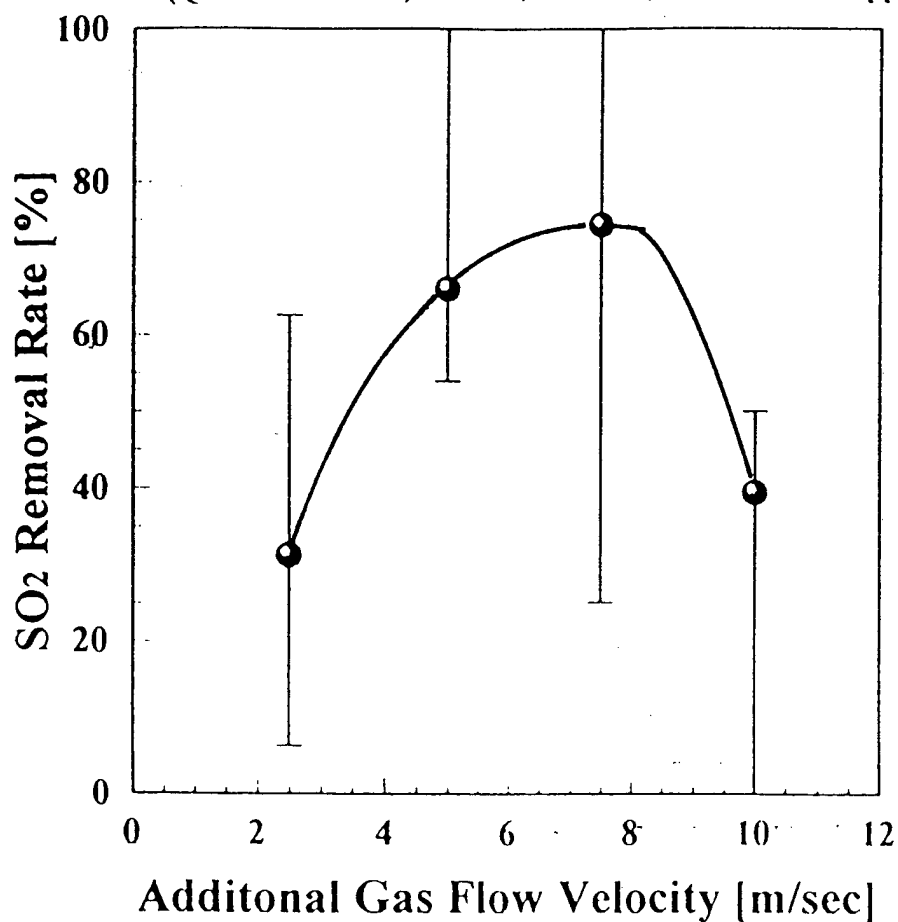
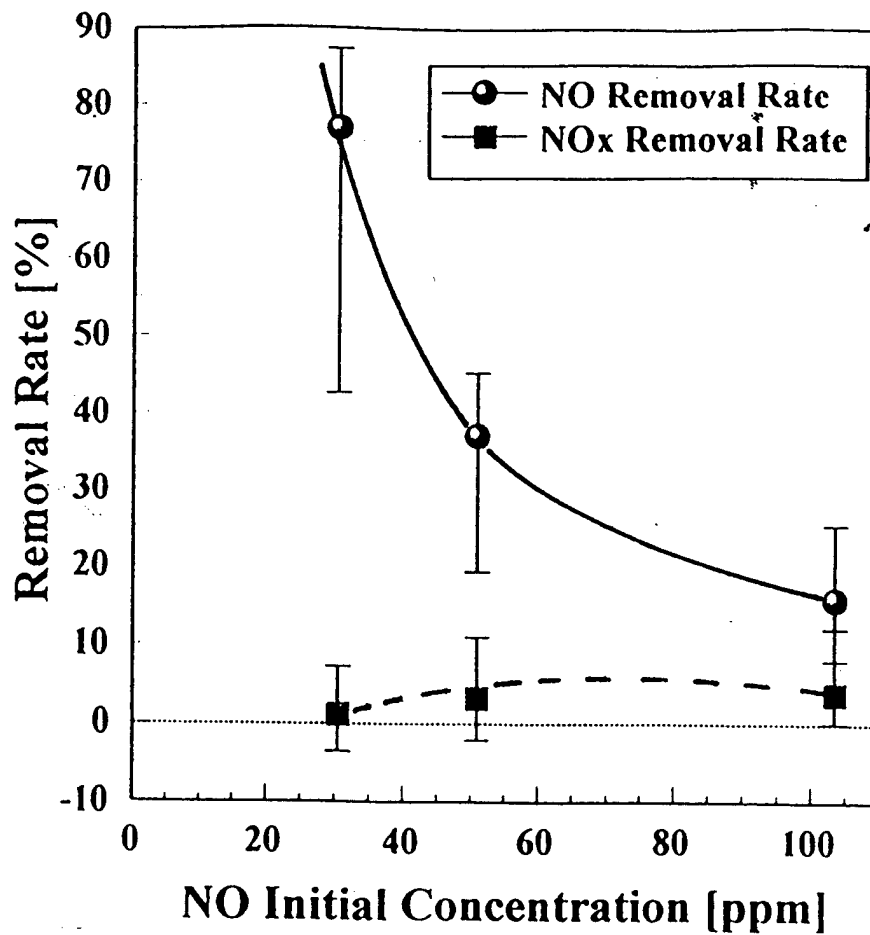
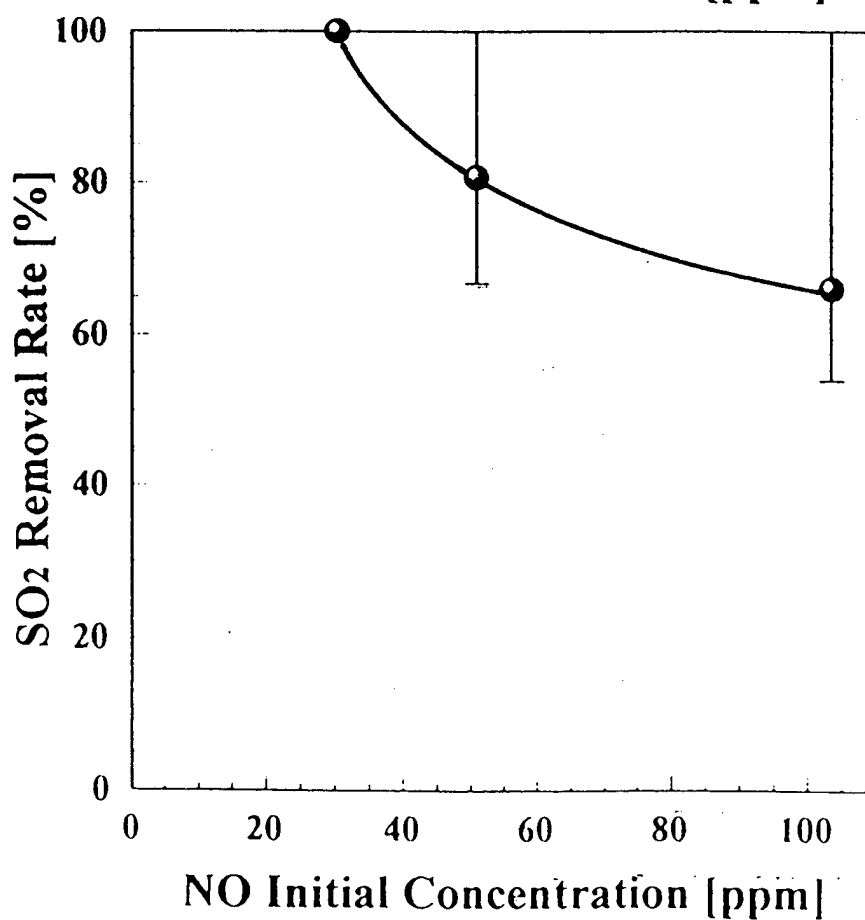


Fig. 2.4 Acid gas removal rate as a function of corona shower system hollow electrode additional gas flow velocity V_{add} . a) NO and NO_x and b) SO_2 .

(a)



(b)



($Q_{\text{air}}=100\text{L/min}$, $v_{\text{add}}=5\text{m/sec}$, $M.R.=1$, $V=23\text{kV}$)

Fig. 2.5 Acid gas removal rate as a function of NO initial concentration in flue gases $[\text{NO}]_0$. a) NO and NO_x and b) SO₂.

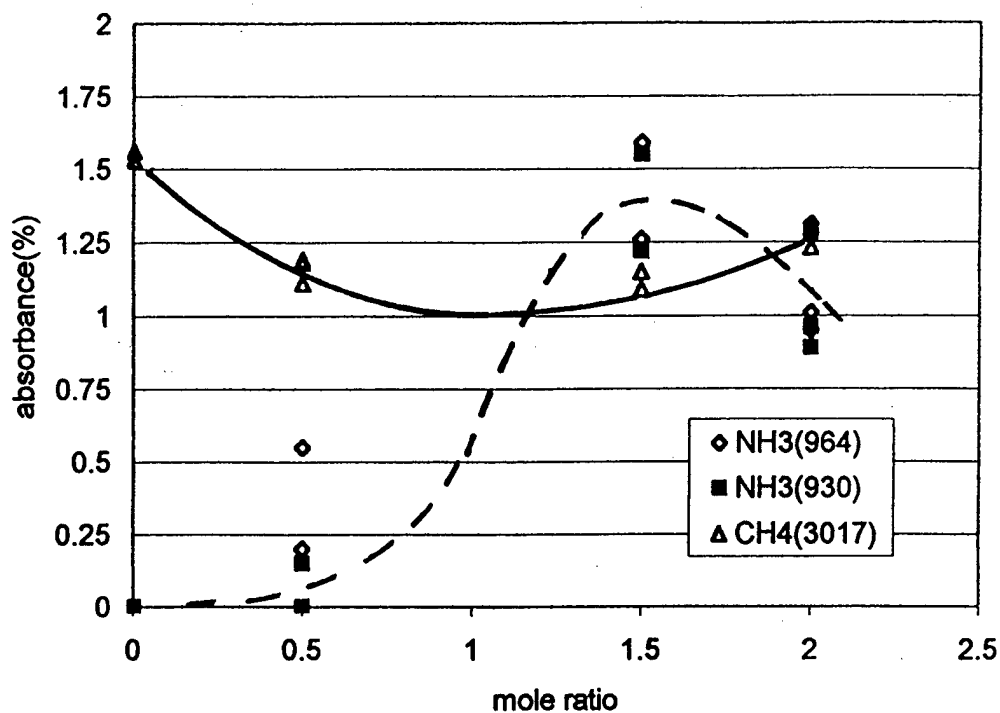


Fig. NH3 absorbance as a function of additional NH3
100ppm 100L/min 5m/sec 23kV

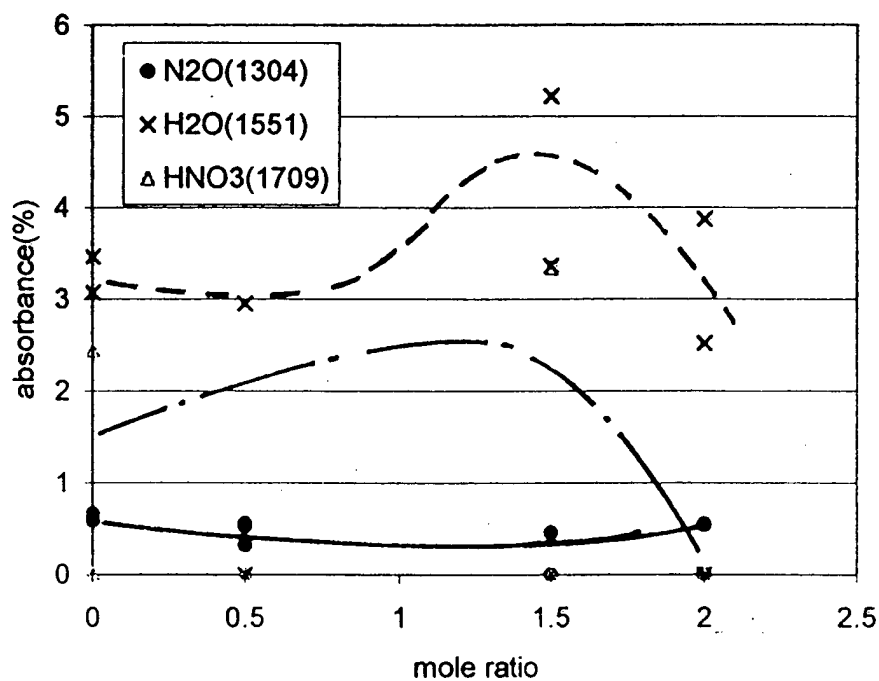


Fig. By-products as a function of additional NH3

Fig. 2.6 Relative concentration (\propto IR absorbance) of a) NH_3 and CH_4 and b) N_2O , H_2O and $\phi\text{-CHO}$ (aldehyde) as a function of ammonia to acid gas molecule ratio at flue gas flow rate $Q_f = 6 \text{ Nm}^3/\text{h}$ (100 L/min), $V = 23 \text{ kV}$, $[\text{NO}]_0 = 100 \text{ ppm}$ and $V_{\text{add}} = 5 \text{ m/s}$.

reaction of methane and ammonia radicals, hence, the removal rates of NO , NO_x , N_2O and CH_4 increase with increasing molecule ratio. However, for the molecule ratio larger than 1, ammonia and their radicals may be mainly consumed for SO_2 removal and $\phi\text{-CHO}$ formations hence NO , NO_x , N_2O and CH_4 removals may be reduced.

By comparison with combustion generated flue gas (without large methane concentration), the removal rate of NO_x is much lower, as has been observed for other engine-generated flue gas plasma treatments [1-4] in spite of effective NO oxidations. The role played by the hydrocarbon under non-thermal plasma treatment should be investigated in detail.

2.4 EXPERIMENTAL RESULTS WITH HYBRID SYSTEM

Acid gas (NO_x , NO and SO_2) removal efficiency as a function of corona shower system applied voltage for NH_3 or CH_4 , and gas temperature at catalyst exist $T_g = 293$ or 234 K are shown in Figs. 2.7 to 2.10. Figure 2.7 shows that acid gas removal efficiencies increase with increasing applied voltage and up to 100% of SO_2 and 62% of NO_x can be removed by the current hybrid system with NH_3 injections. By compared with Figs. 2.2 and 2.7a, the catalyst even operated at room temperature can significantly enhance SO_2 and NO_x removal due to the NH_3 radical generated by the corona shower reactor as has been observed by various investigator using pulsed corona or barrier discharge non-thermal plasma reactor [4,7,8,9]. For the NO_x removal, the role of catalyst is mainly NO_2 catalytic reductions (see Figs. 2.7a and 2.7b) and adsorption/catalytic reactions for SO_2 . By comparison between Figs. 2.7 and 2.8, the effect of heating catalyst (monitored by catalyst exist gas temperatures) shows slightly negative effects on NO_x removal but no effects on SO_2 removals.

Figures 2.9 and 2.10 show the effects of heating catalyst on the CH_4 injection cases. The results show that the acid gas removal efficiency increases with increasing applied voltage but no

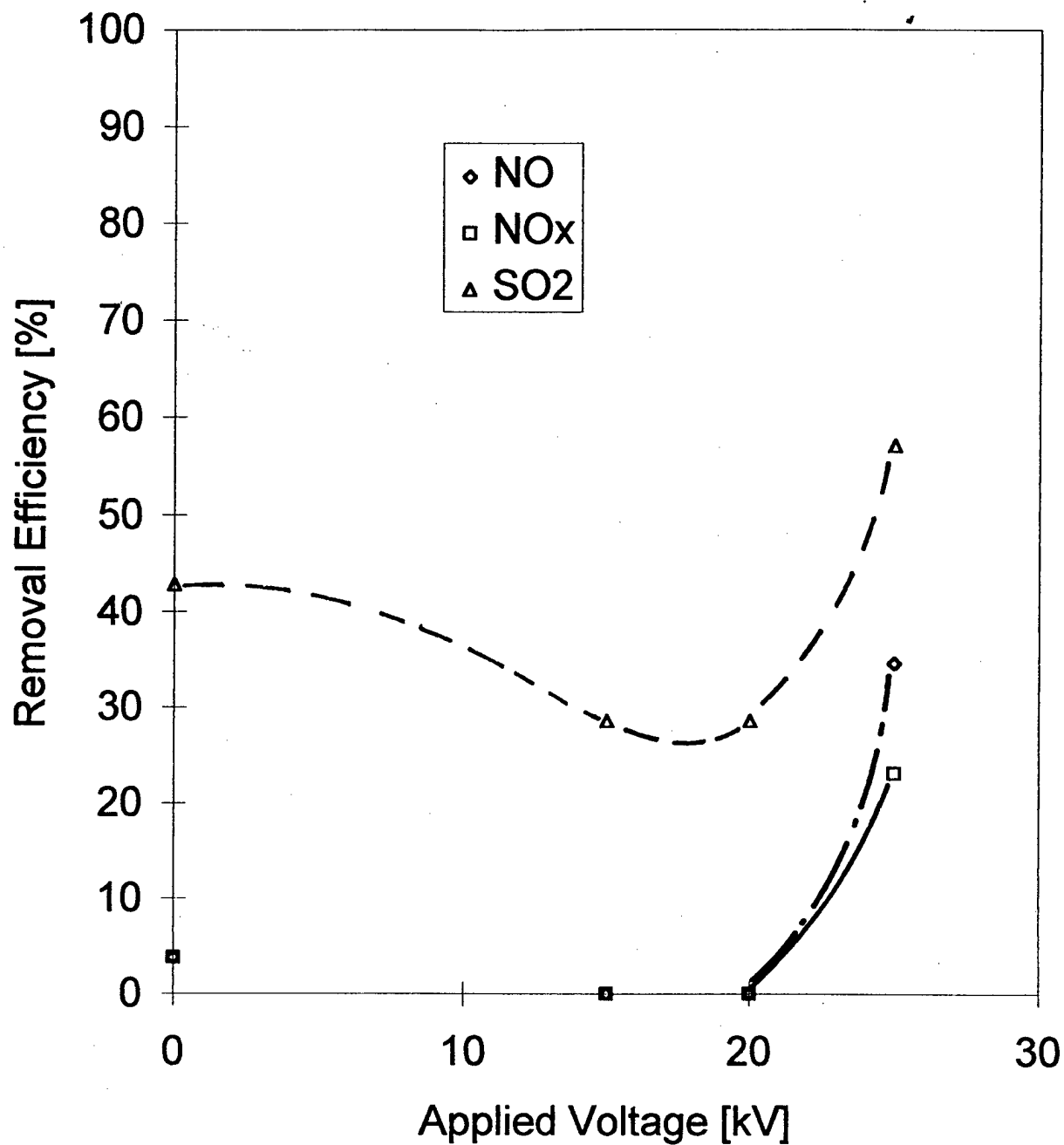


Fig. 2.7 Removal efficiency as a function of applied voltage without heating and NH_3 injection (before Catalysis)

Fig. 2.7 Acid gas removal efficiency as a function of applied voltage for NH_3 injections in hybrid systems at $T_g = 293\text{K}$. a) After corona shower reactor; b) after catalyst; and c) after ESP.

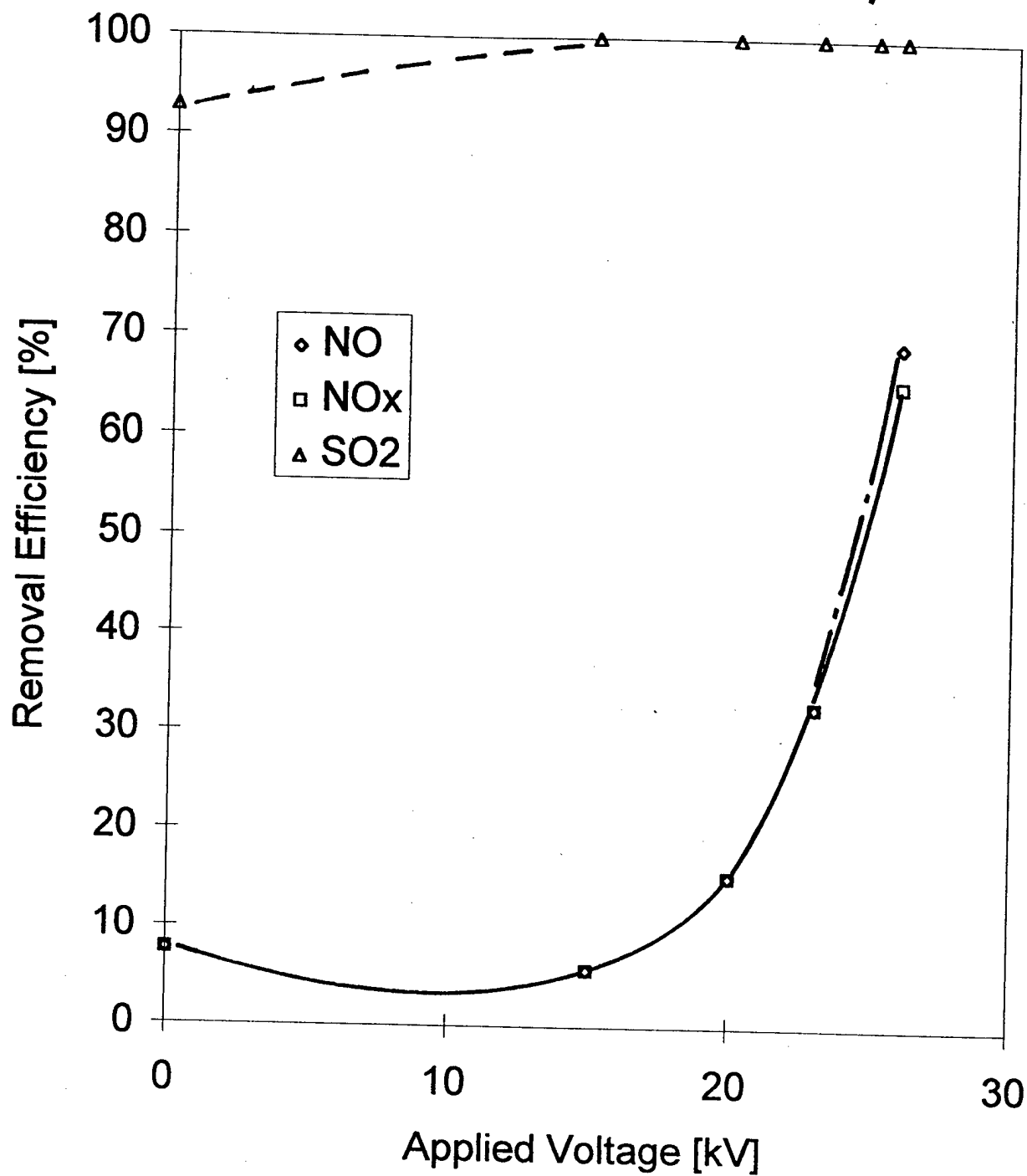


Fig. 2.7 Removal efficiency as a function of applied voltage without heating and NH3 injection (after Catalysis)

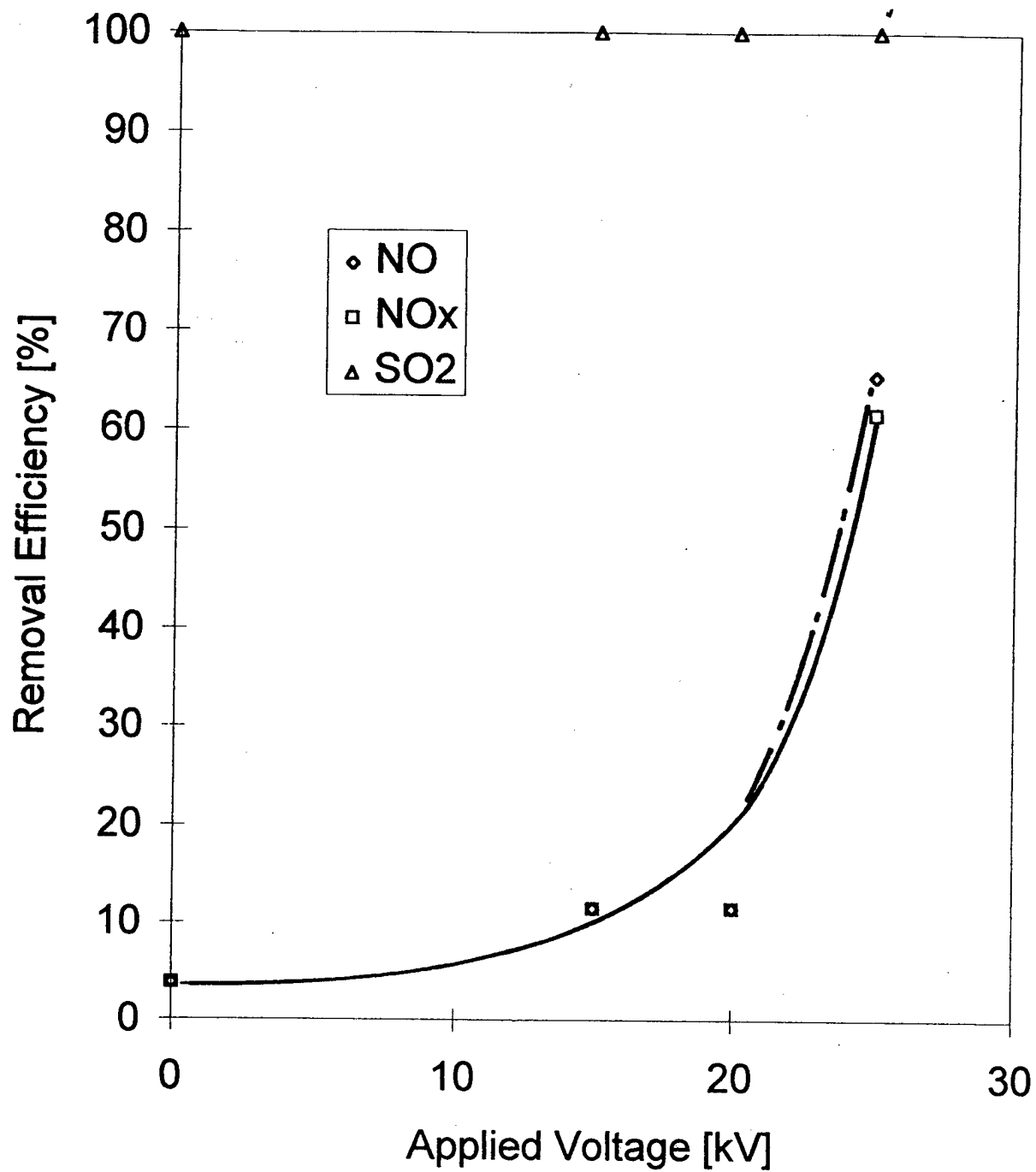


Fig. 2.7 Removal efficiency as a function of applied voltage without heating and NH3 injection (after ESP)

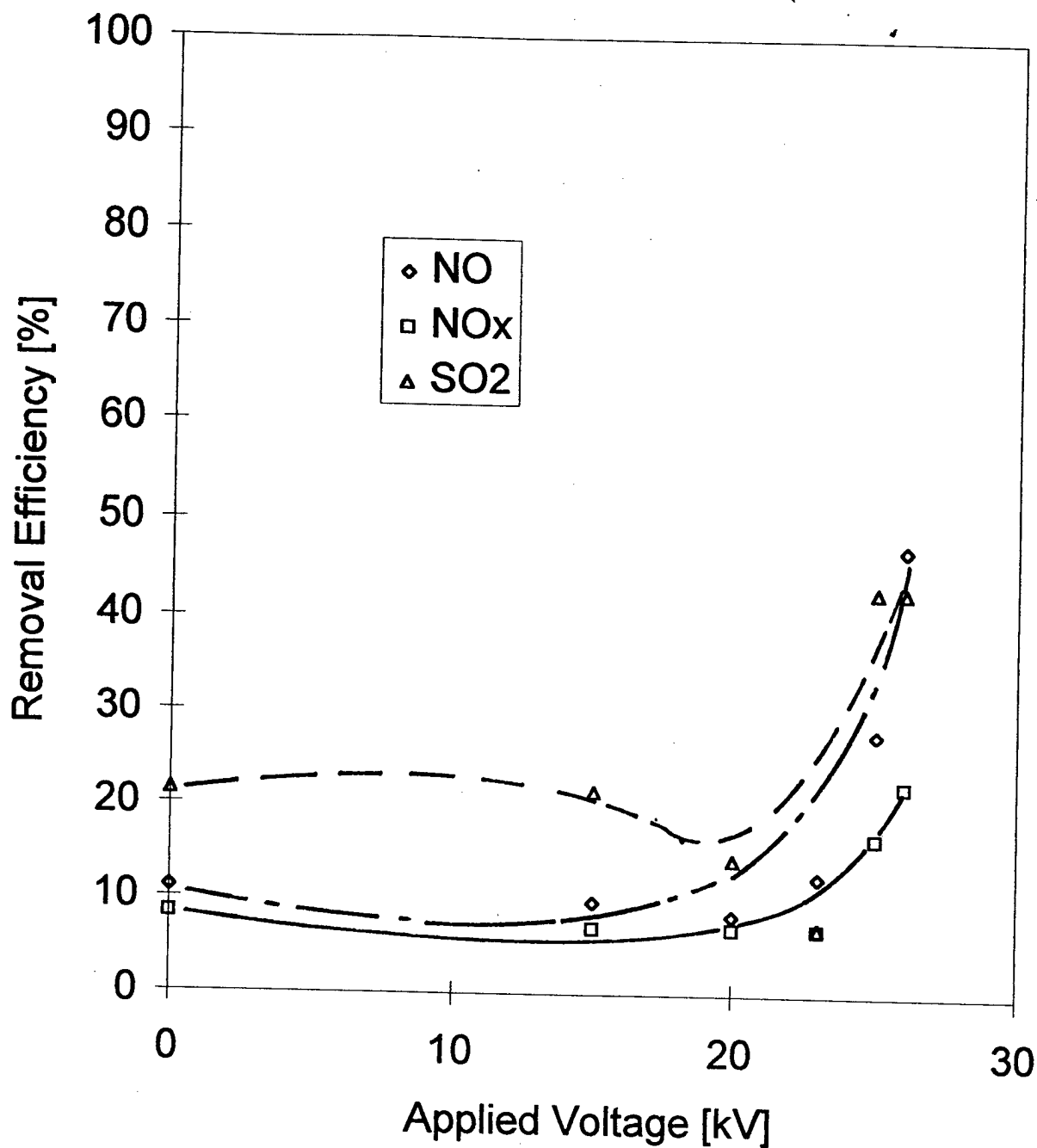


Fig.28a Removal efficiency as a function of applied voltage with two heating tape and NH₃ injection (before Catalysis)

Fig. 2.8 Acid gas removal efficiency as a function of applied voltage for NH₃ injections in hybrid systems at $T_g = 324K$. a) After corona shower reactor; b) after catalyst; and c) after ESP.

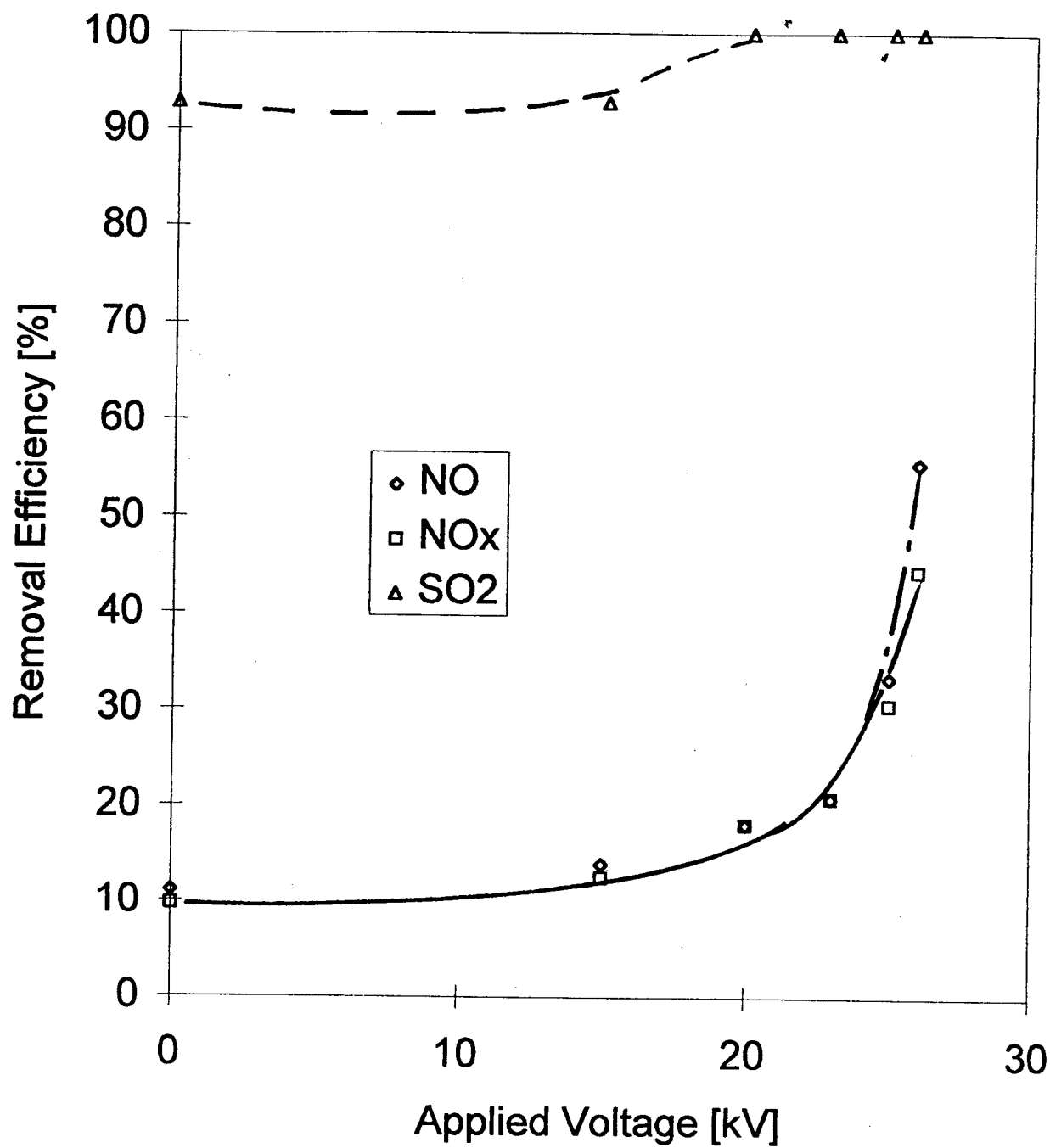


Fig.28b Removal efficiency as a function of applied voltage with two heating tape and NH3 injection (after Catalysis)

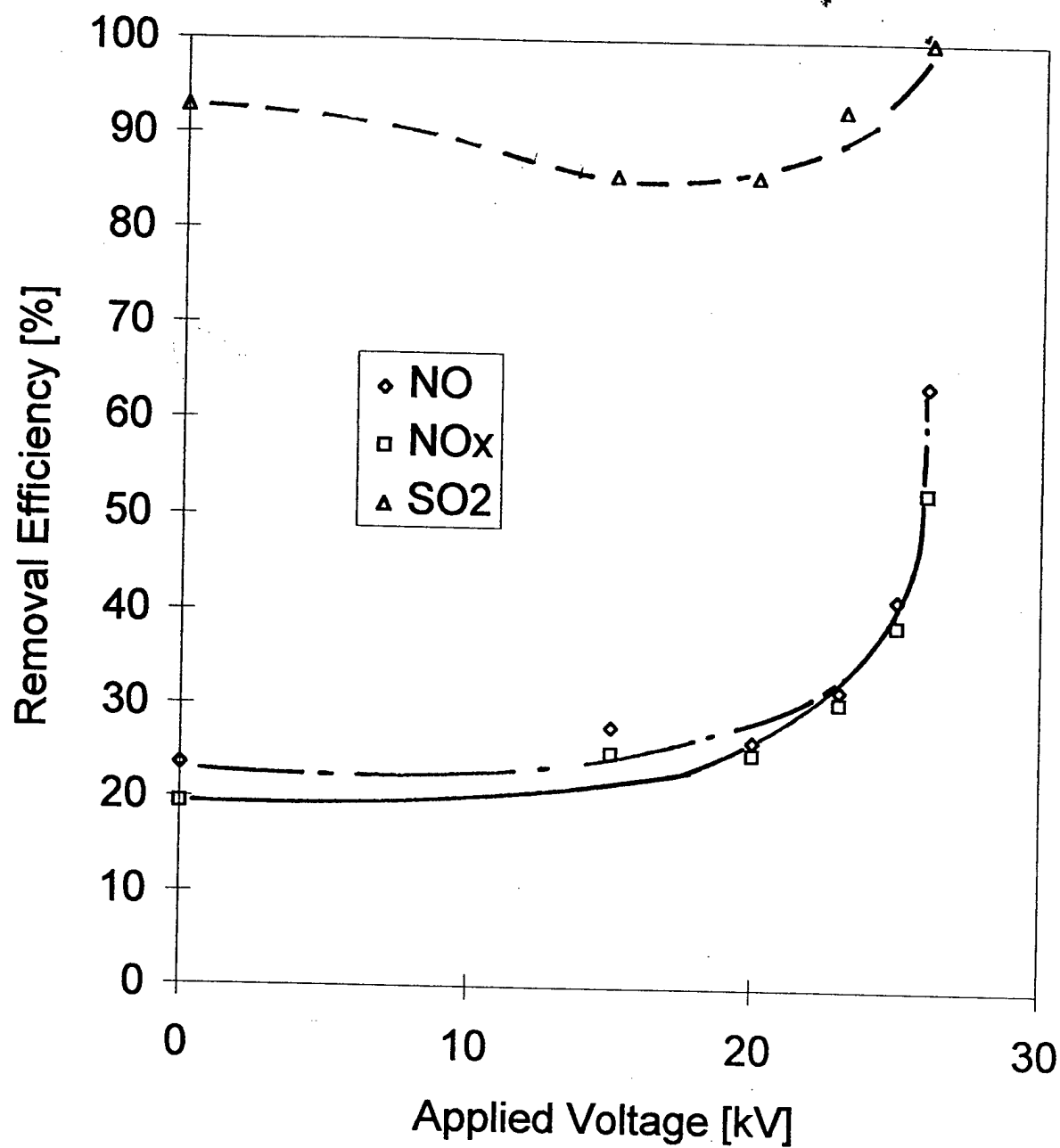


Fig. 2.9c Removal efficiency as a function of applied voltage with two heating tape and NH₃ injection (after ESP)

significant catalyst and heating effects on the NO_x removals. However, SO_2 removal efficiency is significantly enhanced by the adsorption effect of catalyst, where SO_2 removal efficiency decreases with increasing catalyst heating due to the decreasing adsorption capability of ceramic catalyst under higher temperature. Maximum SO_2 removal efficiency is same for NH_3 or CH_4 injections but NO_x removal with NH_3 injections is much higher compared with CH_4 injections. 50–50% mixture of NH_3 and CH_4 is also used as an injection gas to the corona shower system, however, the results are only slightly better compared with CH_4 injection cases.

2.5 CONCLUDING REMARKS

An experimental investigation has been conducted to remove acid gases from stationary engine flue gas and the following concluding remarks are obtained: 1) NO , NO_x and SO_2 removal rates increase with increasing applied voltage and decrease with increasing NO initial concentration in the flue gases; (2) NO , NO_x and SO_2 removal rates non-monotonically depend on corona shower system additional gas flow velocity due to the mixing effects where the maximum removal rates are observed near 8 m/s; (3) SO_2 removal rates increase with increasing ammonia to acid gas molecule ratio while NO and NO_x non-monotonically depend on molecule ratio; (4) Ammonia and methane slips non-monotonically depend on ammonia to acid gas molecule ratio; (5) Trace unwanted discharge by-products significantly depend on ammonia to acid gas molecule ratio and only N_2O and $\phi\text{-CHO}$ (aldehydes) are observed; (6) Significant amounts of aerosol particles are formed during the acid gas removal processes; (7) The effects of catalytic reactions even in room temperature is significant with NH_3 injections but not significant for CH_4 injections for NO_x removals; and (8) SO_2 removal efficiency is significantly enhanced by adsorption/catalytic reactions of catalyst.

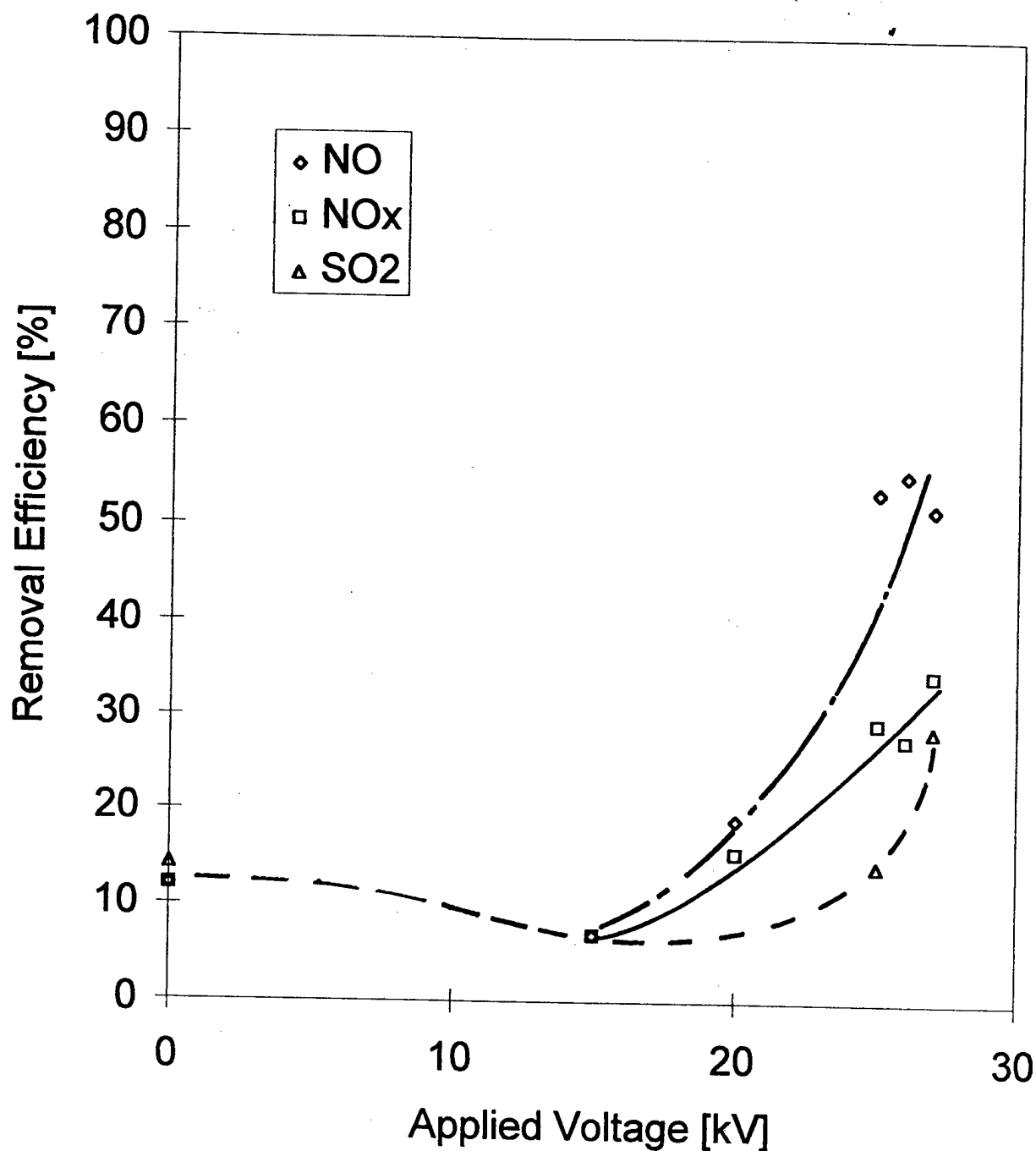


Fig. 2.9 Removal efficiency as a function of applied voltage without heating and CH₄ injection (before Catalysis)

Fig. 2.9 Acid gas removal efficiency as a function of applied voltage for CH₄ injections in hybrid systems at $T_g = 293K$. a) After corona shower reactor; b) after catalyst; and c) after ESP.

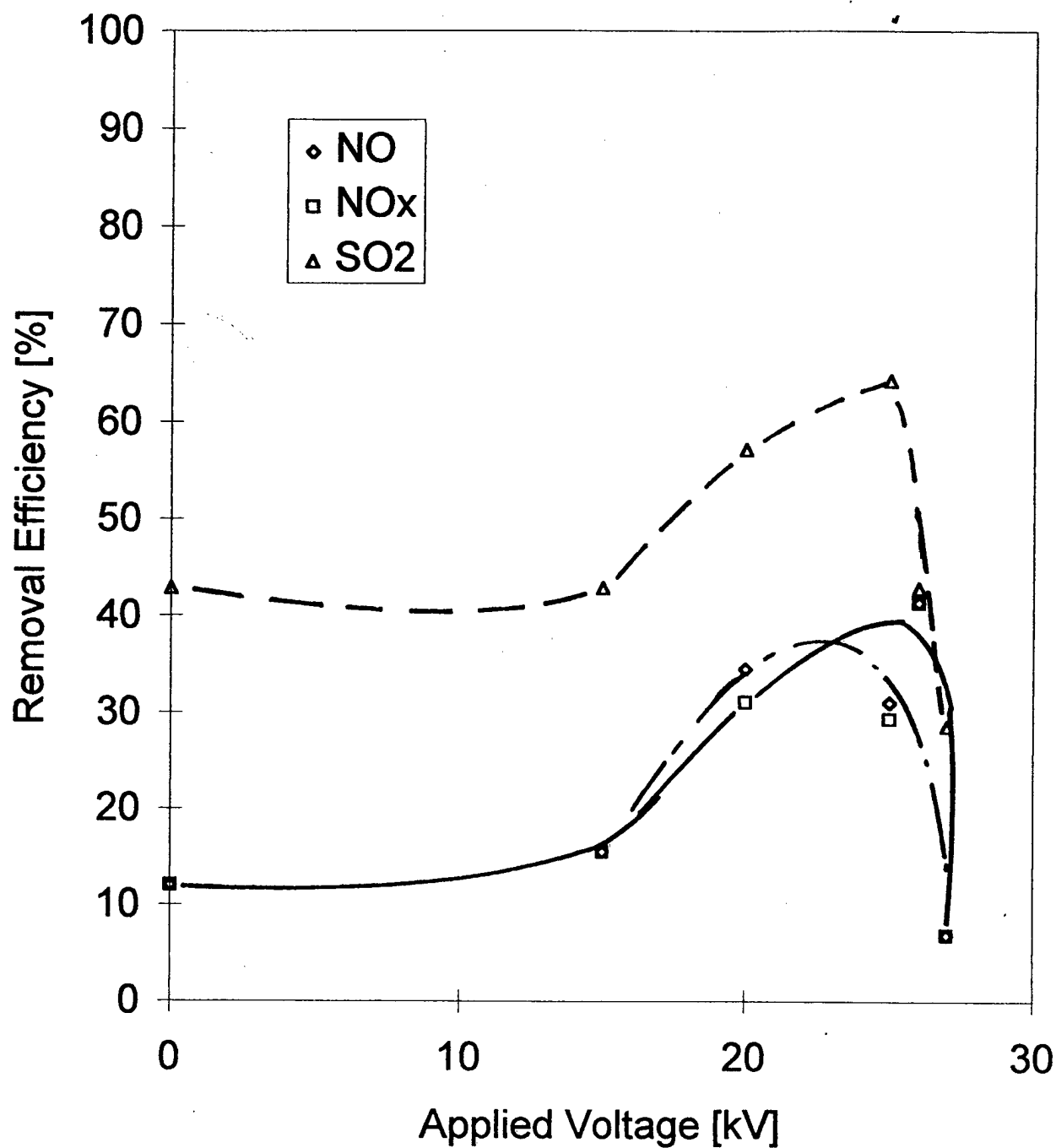


Fig. 2.9 Removal efficiency as a function of applied voltage without heating and CH₄ injection (after Catalysis)

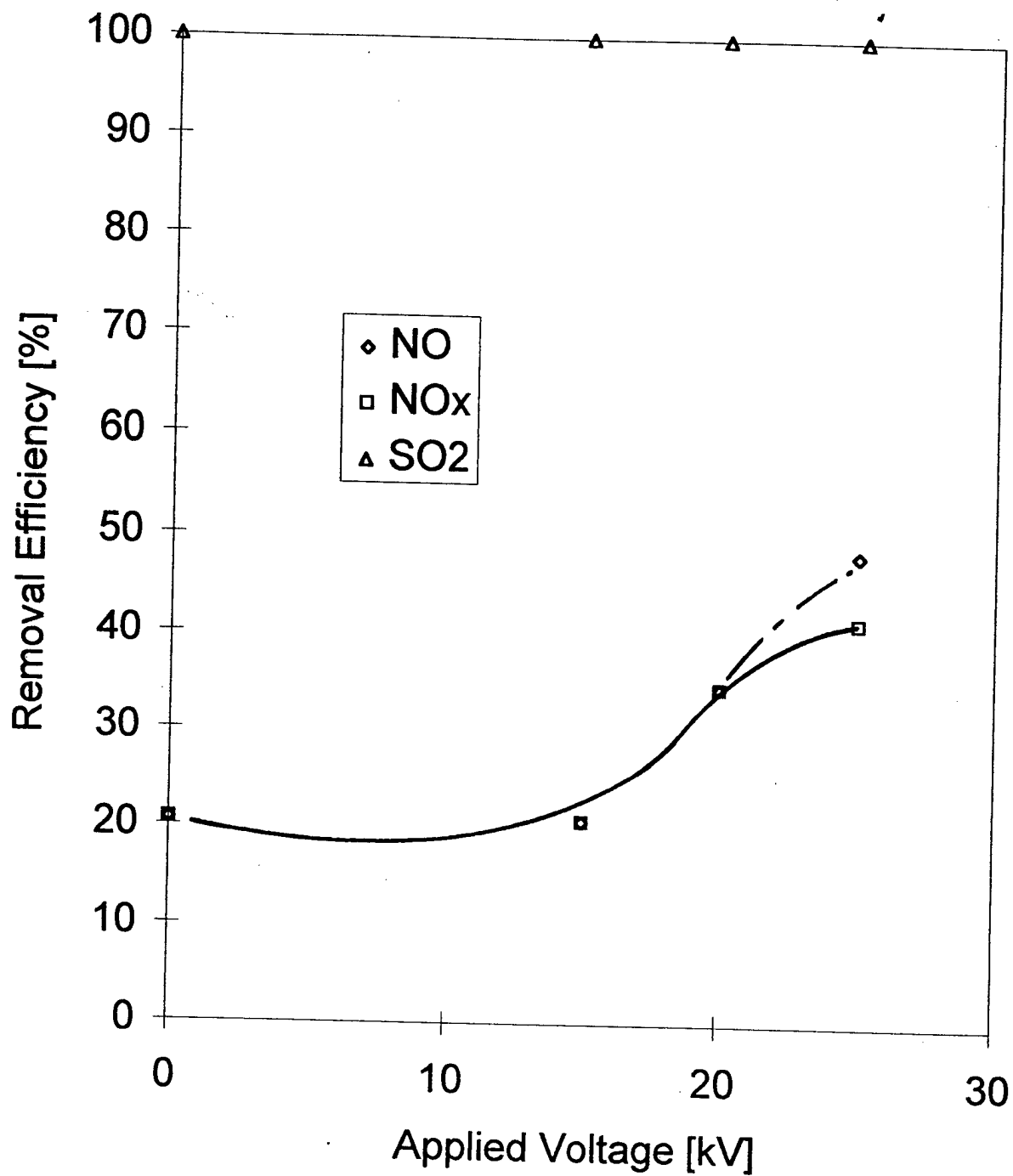


Fig.C 2.9 Removal efficiency as a function of applied voltage without heating and CH4 injection (after ESP)

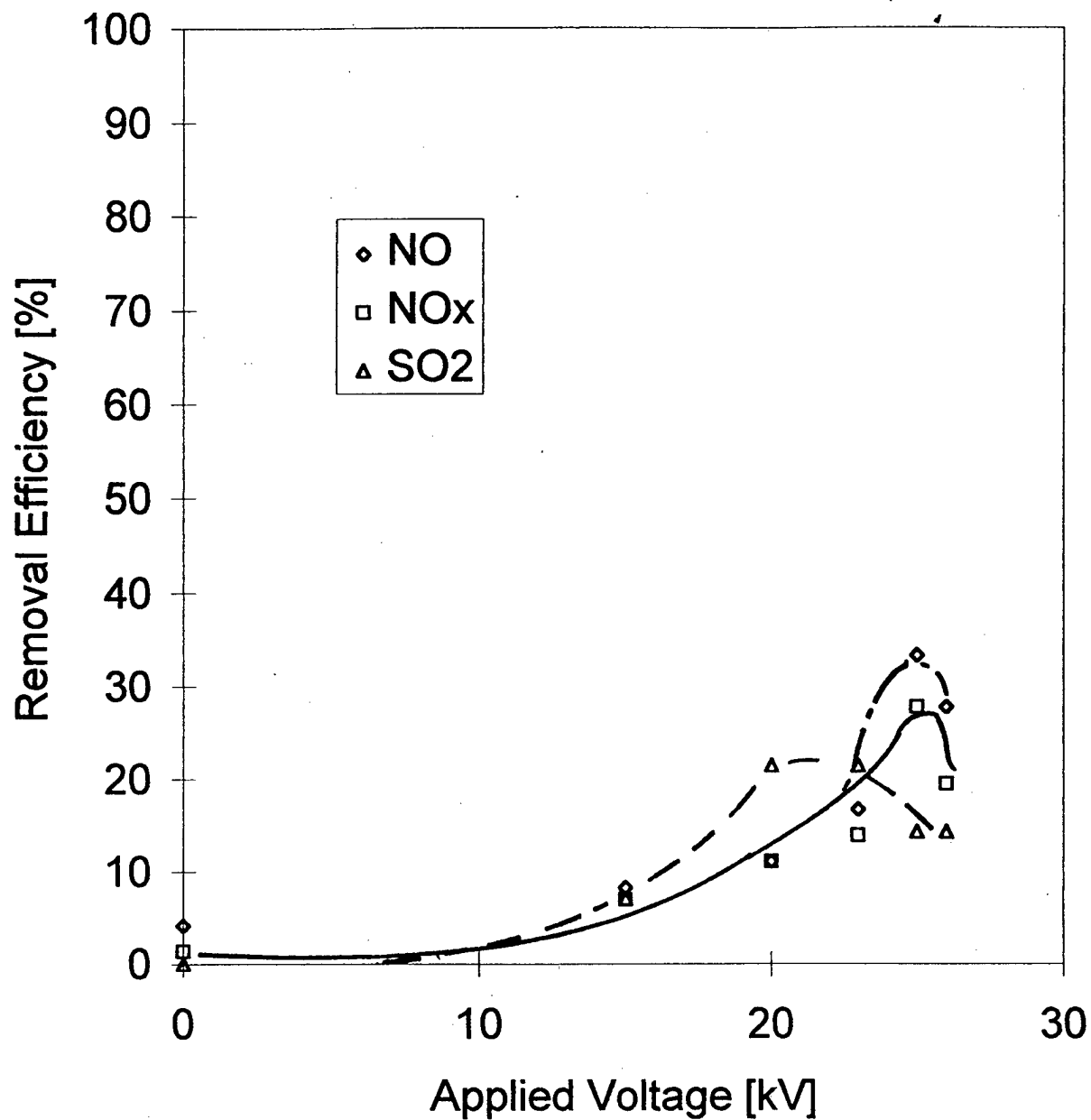


Fig. 2.10 Removal efficiency as a function of applied voltage with two heating tape and CH₄ injection (before Catalysis)

Fig. 2.10 Acid gas removal efficiency as a function of applied voltage for CH₄ injections in hybrid systems at $T_g = 324K$. a) After corona shower reactor; b) after catalyst; and c) after ESP.

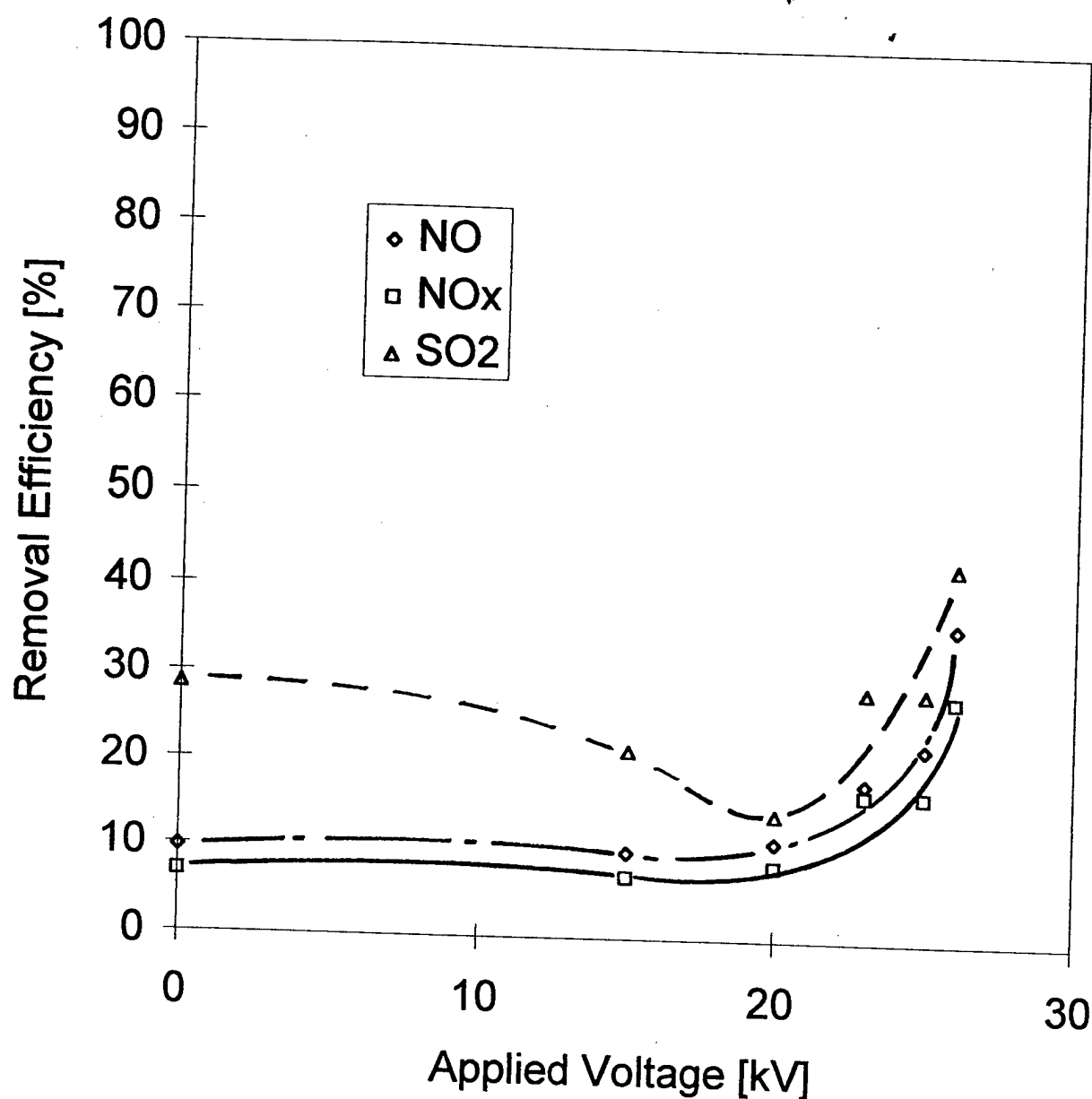


Fig.20b Removal efficiency as a function of applied voltage with two heating tape and CH₄ injection (after Catalysis)

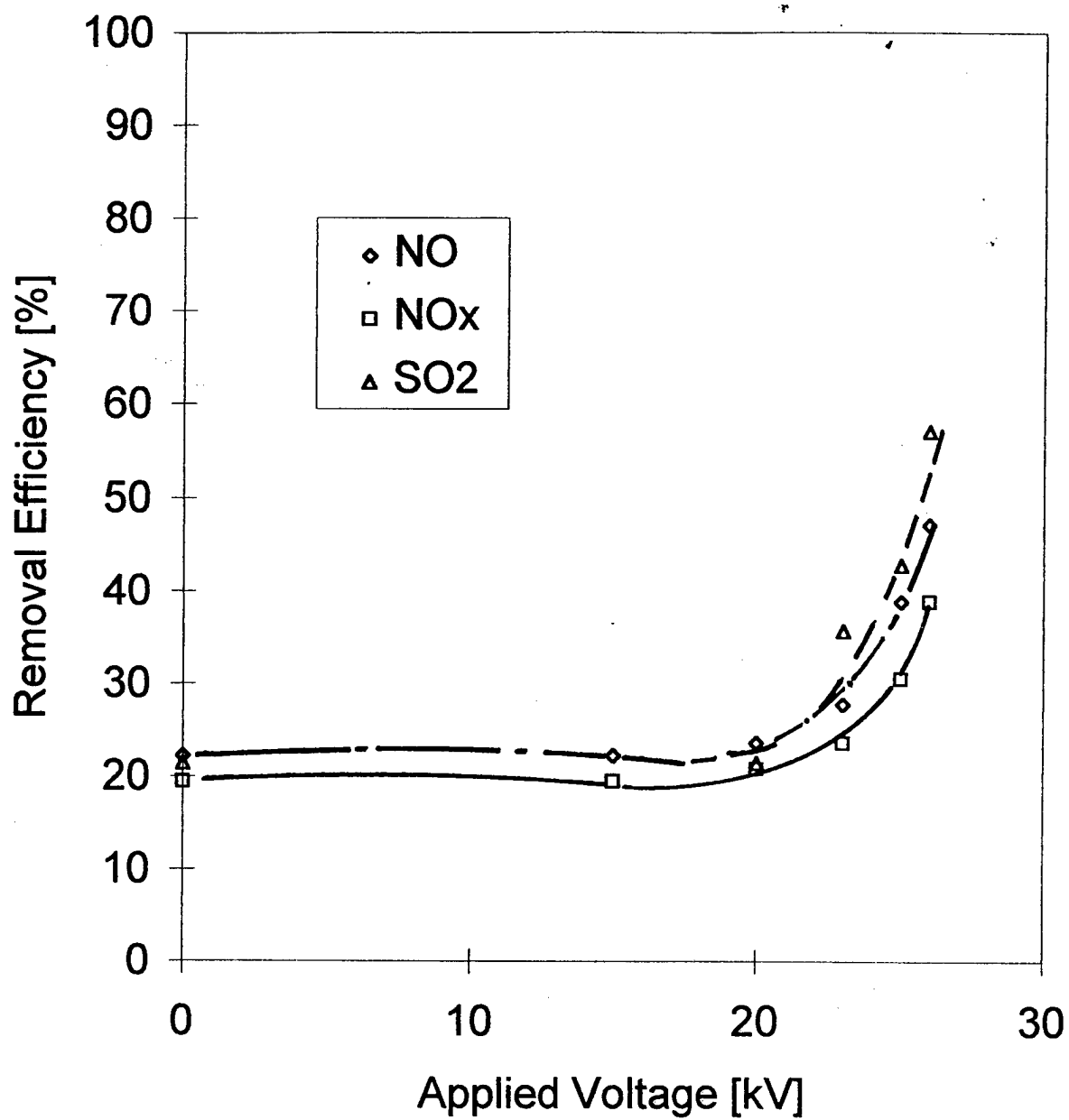


Fig.2.10 Removal efficiency as a function of applied voltage with two heating tape and CH₄ injection (after ESP)

REFERENCES

1. K. Urashima, H. Miyamoto and T. Ito, Comb. Sci. & Tech., 133, 89-100 (1998).
2. M. Higashi, S. Uchida, N. Suzuki and K. Fujii, IEEE Trans. Plasma Sci., 20, 1-12, 1992.
3. B.M. Penetrante, J.N. Bardsley and M.C. Hsiao, Japanese J. Appl. Phys., 36, 5007-5017, 1997.
4. T. Hammer, S. Broer and T. Kishimoto, J. Adv. Oxid. Tech., 3 (in press, 1998).
5. J.S. Chang, J. Aerosol Sci., 20, 1087-1090, 1989.
6. T. Ohkubo, S. Kanazawa, Y. Nomoto, J.S. Chang and T. Adachi, IEEE Trans. Ind. Appl., 20, 1058-1062, 1996.
7. T. Oda and K. Shimizu, J. Adv. Oxid. Tech., 3 (in press, 1998).
8. H. Kim, S. Katsura and A. Mizuno, J. Adv. Oxid. Tech., 3 (in press, 1998).
9. J. Howard, J. Adv. Oxid. Tech. (submitted, 1998).
10. S. Kanazawa, J.S. Chang, G.F. Round, G. Sheng, T. Ohkubo, Y. Nomoto and T. Adachi, J. Electrostatics, 40&41, 651-656 (1997); and Comb. Sci. & Tech., 133, 93-105 (1998).

PART 3.

PRELIMINARY CONCEPTUAL DESIGN OF PILOT PLANT TEST FOR PLASMA JET ENGINE TEST CELL FLUE GAS TREATMENTS

ABSTRACT

Preliminary conceptual design has been conducted for the pilot plant test cell flue gas cleaning in DOE facilities. Pilot plant will be directed 340 Nm³/h of flue gases from the main jet engine test cell exhaust duct by 20 cm i.d. flow tubes. Fourteen flow channel corona shower reactor (140×60×120 cm) and 30 flow channel-5 section electrostatic precipitator are required for the acid gas treatments.

3.1 INTRODUCTION

In order to treat the jet engine (JETC) and the cruise missile test cells (CMTC), 10⁴–10⁶ scfm (or 2×10⁴ to 2×10⁶ Nm³/h), flue gas flow rate must be treated. Hence, 10² to 10³ scfm level pilot plant must be constructed. In this section, a preliminary conceptual design has been conducted for the pilot plant for the JETC/CMTC flue gas treatments.

3.2 PROPOSED DESIGN AND SPECIFICATIONS

Based on the large bench scale tests (LBS) conducted at 12 Nm³/h, the simple scale-up pilot test selected in 340 Nm³/h flue gas flow rate. Under this condition, the length of LBS corona shower system can be used with slightly larger height and length with multi-flow channel. Schematics of proposed pilot test facility is shown in Fig. 3.1. The part of JETC flue gas will be diverted to the pilot

plant through the 20 cm i.d. flow tube with electromagnetic gate valves (EMGV).⁴ In order to obtain near fully developed flow, the corona shower reactor (CSR) will be installed 4 m downstream of the EMGV and electrostatic precipitator (ESP) will be installed again 4 m downstream of CSR. Independent NO_x , SO_x and VOC meters will be installed 1 m downstream of CSR and 1 m downstream of ESP.

A detail of corona shower reactor is shown in Fig. 3.2. Corona shower reactor dimension is (140×60×120 cm) with 14 flow channels. Five 60 cm long corona shower electrodes/channel will be installed. Corona shower system will be driven by 6 kW dc power supply (40 kV×150 mA) or by seven 1 kW power supplies (40 kV×25 mA). Air- NH_3 mixture gas will be fed through the corona shower electrodes via flow controllers (FC).

A detail of the wire-plate type electrostatic precipitator is shown in Fig. 3.3. The dimension of the five section ESP is (150×60×80 cm) and 30 flow channels. ESP is driven by the 6 kW dc power supply.

3.3 RECOMMENDATION

In order to conduct pilot plant tests, the site visit must be conducted before the conceptual design stage. The conceptual design for the plant will take one month, and the following detailed design will require two months. Construction of corona shower reactor and electrostatic precipitator will take two to three months. Integration of the system into the pilot plant site will take one to two months. In total, 8 to 10 months are required to construct this pilot plant. If we plan to conduct this pilot plant test, 12 to 18 months are required for the project.

EXPERIMENTAL LOOP

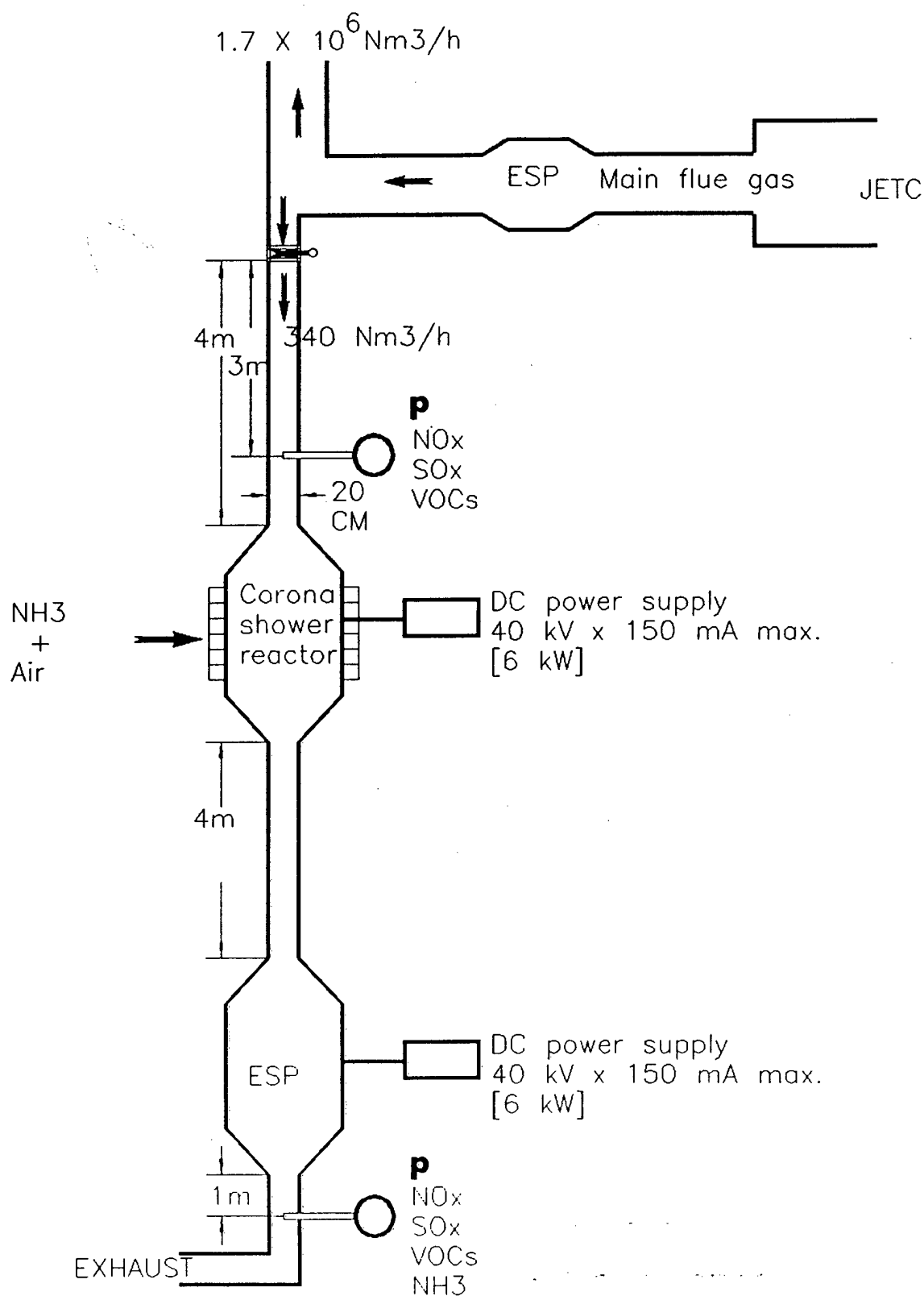


Fig. 3.1

Schematics of pilot plant test loop.

CORONA SHOWER REACTOR (140 X 60 X 120 CM)

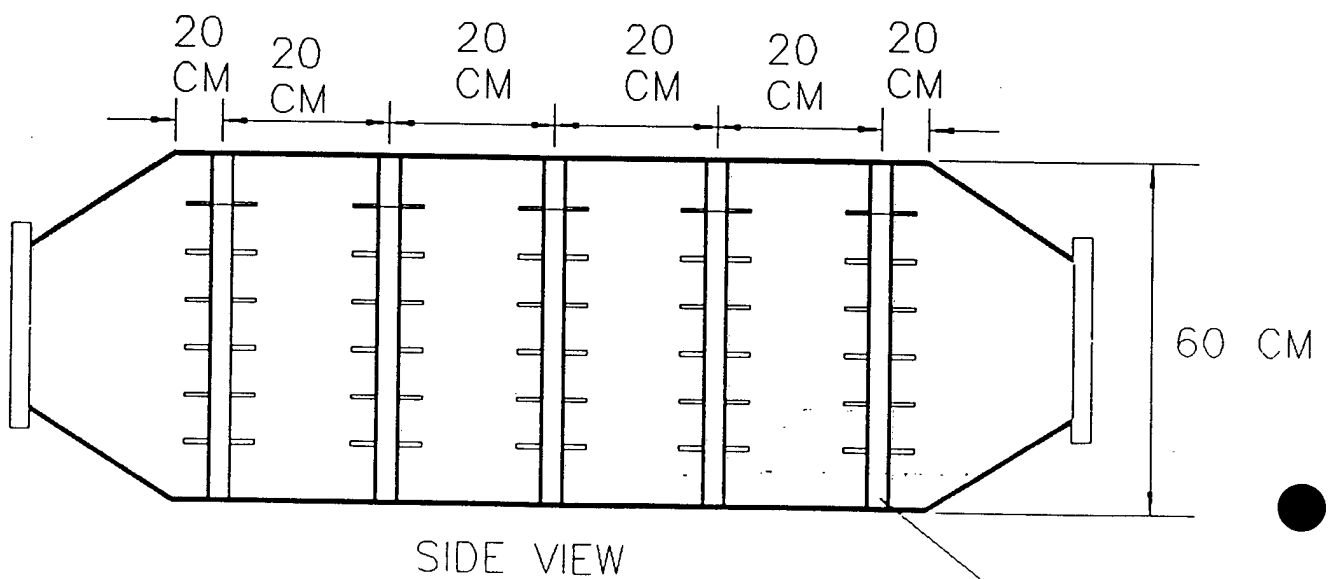
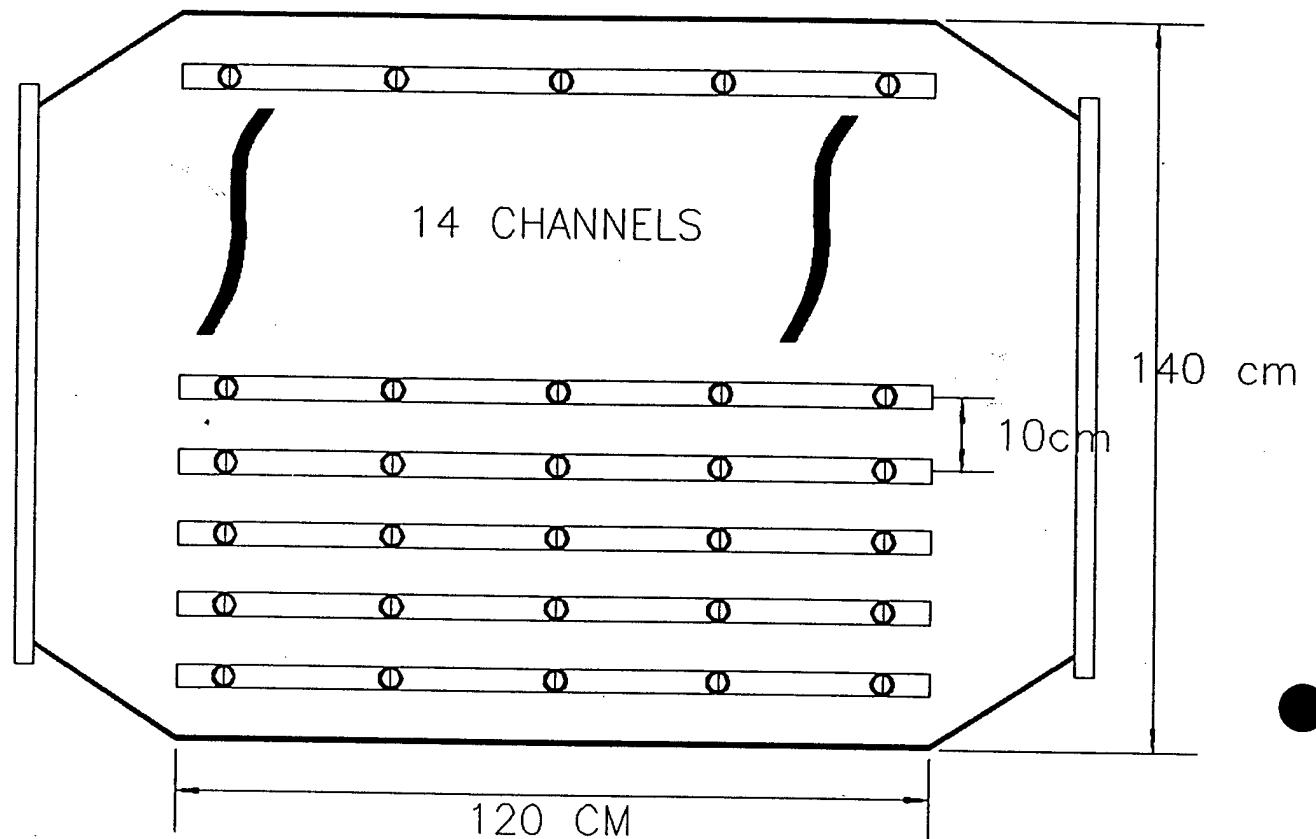


Fig. 3.2

Details of corona shower reactor.

CORONA SHOWER
ELECTRODE

ELECTROSTATIC PRECIPITATOR (150 X 60 X 80 CM)

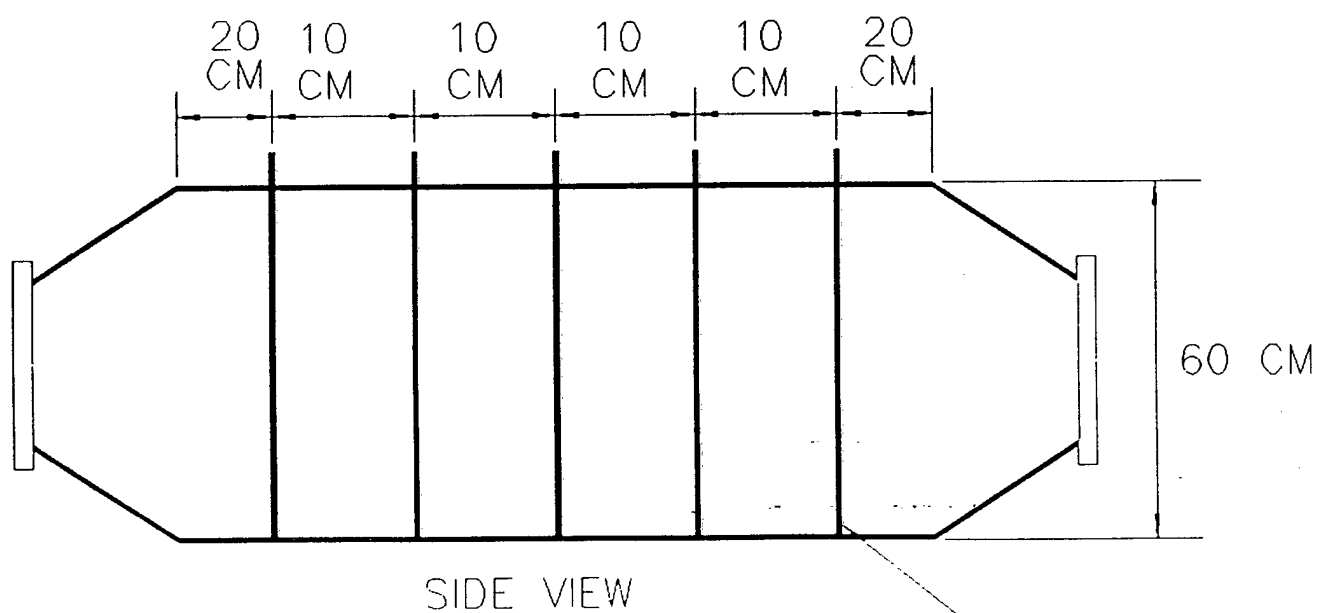
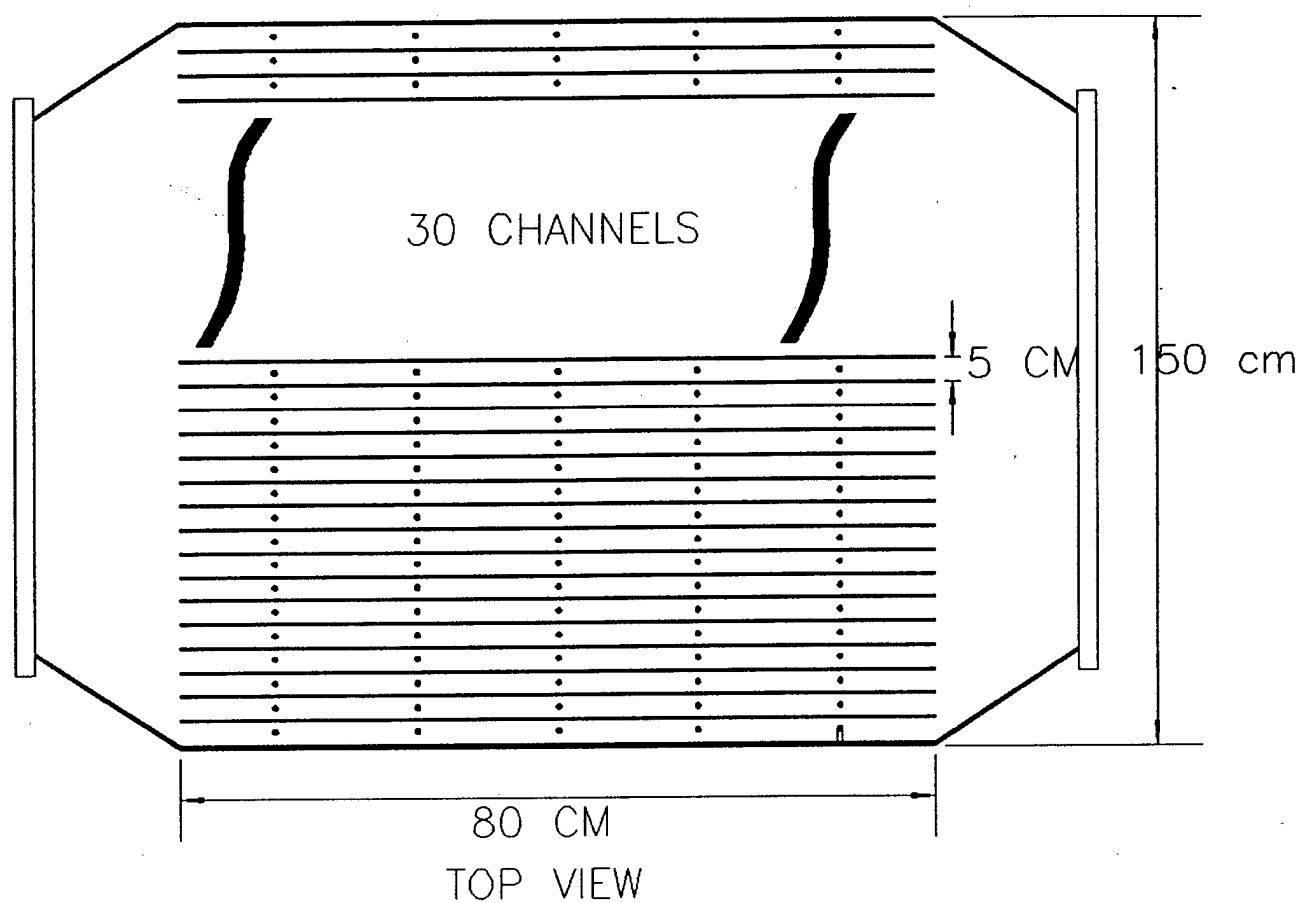


Fig. 3.3

Details of electrostatic precipitator.

CORONA WIRE

APPENDIX

REVIEW OF CATALYSTS/ADSORBENTS FOR GASEOUS POLLUTION CONTROL IN JETC

ABSTRACT

Review of existing catalysts and adsorbents for gaseous pollution control has been conducted. Several ceramic base and three-way metal base catalysts were tested and used in diesel flue gas emission control, however, only $\text{Sr}_x\text{La}_x\text{CoO}_3$ catalysts were small-scale tested in JETCs at U.S. Air Force Armstrong Laboratory. Based on bench-scale tests, most of the catalysts require operations above 300°C , hence gas reheaters are required for the JETC/CMTC applications. No detailed sulphur poison problems and particulate matter effects were discussed in references.

A.1 INTRODUCTION

Catalysts are widely used in the treatment of NO_x in automobile exhaust and coal/oil/natural gas-fired power plant flue gases. The operation of catalysts required normally operated at higher gas temperatures ($>300^\circ\text{C}$) or moderate gas temperature with additives such as ammonia ($>250^\circ\text{C}$). More recently, a major effort for R&D in gaseous pollution control is lowering the catalyst operation temperature and the application to diesel engine flue gases. In this section, the review of existing catalysts has been conducted and applications to JETC examined.

A.2 LIST OF CATALYSTS

A list of catalysts recently developed for the control of gaseous pollutant is shown in Table A, where the adsorbent for the gaseous pollution control also listed in this table. Ceramic base and

three-way metal base catalysts were mainly used and applications to diesel engine flue gases were tried. However, most of the catalysts studied are still operating in higher gas temperatures ($>250^{\circ}\text{C}$) and no detailed sulphur poison problems are conducted. An application to JETCs only conducted by U.S. Air Force Armstrong Laboratory in small scale using metal perovskite catalysts ($\text{Sr}_x\text{La}_x\text{CoO}_3$) for NO_x in N_2 . However, no effects of VOCs, SO_2 and particulate matter in flue gas were well investigated.

A.3 CONCLUDING REMARKS

Since JETC/CMTC flue gas contains SO_2 and VOCs, an application of existing catalysts must be carefully studied. Hence, three different options are proposed as follows:

1. Using wet scrubber-reheater-catalysts system;
2. Using electrostatic precipitator-reheater-catalysts system;
3. Using plasma reactor-catalyst system.

Based on the economic evaluations in Section 1, Options 1 and 2 are much more expensive compared with the plasma system. Hence, the third option without gas reheater should be tested.

Table A List of Catalysts for Pollution Control

Company	Sources	Materials	Gases	Flow rate	De-%	Date	Commer.	Ref.	Comment
ACCEL Catalysts, Inc., USA	automobile	metal-Pt-Rh	NOx, HC, CO	?	-	94	N/A	5	Metal-Supported Metal(MSM), \$50,000 contract
Air Force, Armstrong Lab., USA	JETCs	SrxLal-xCoO3	NO, NO2, N2	?	90, -, -	94	N/A	4	
Allis Mineral Systems, USA & ISGS Appli. Reser. Lab.	waste incinerator	activated carbon	SOx, NOx	?	90, 80	July'95	N/A	16	Hg, dioxins, furans
AVL-LIST, USA	diesel (fuel)	Zeolite	NOx	?	17-30	Jul.96	engine fuel system	12	modified fuel system fuel economy not given
Caralytica Combustion systems, USA	gas turbine engine	SCRs	NOx	?	80	98	yes	3	XONON®
Catalytica Combustion system Inc. & Allison Engine Co., USA	power generation, 4.5-11MW		NOx, CO, HC	?	5ppm	Apr.96	N/A	2	\$3.5mill. contract, \$82.5 mill. for 5-7 years
Cosmo Research Institute, Japan	diesel	Al2O3(A)	NOx (1000ppm)-O2(10%)-CH3OH (1000ppm)-C3H6 (330ppm)	200kW (7200h-1)	10-70 (250-300°C)	97	yes	23	
	diesel	Al2O3(B)	NOx (1000ppm)-CH3OH (1000ppm)	200kW (7200h-1)	45-90 (375-440°C)	97	yes	23	

List of Catalysts for Pollution Control

Company	Sources	Materials	Gases	Flow rate	De-%	Date	Commer.	Ref.	Comment
Cycle-Thermal, Inc & Advanced Environmental System, Inc., USA	solvent laden fumes	thermal/ catalytic oxidizer	Cl-VOCs		>99		yes	13	VOC concentrators, Fibered Mist Collection System
Degussa, Germany	Synthetic gas	zeolite impregnated with IB and VIII elements	C3H6 / C3H8	40,000h-1	10-85 (unaged), 10-55 (aged)	Jul.96	N/A	12	HC/NOx=2400ppmC/27 0ppm
	stationary	ceramic and metal-Pt-Rh	NOx, CO, HC	-			yes	11	HDC, PCE, TCE, MCl, MBr
	diesel	Pt-Zeolite	800ppm C4H8/C4H 10(2/1) + exhaust HC	transient space velocity	19 (unaged) 23 (aged)	Jul.96	N/A	12	vehicle test, 50hr catalyst aging
Hokkaido Univ., Japan	diesel	Cu-ZSM-5	ethylene	20,000	25/50(wit hout/with ethylene)	Jul.96	bottle	12	water and particulate removed
	diesel (light oil)	Cu-ZSM-5	NOx	20,000	80	Jul.96	drip	12	
Honda Tech. Inst. Co., Japan	2 cycle engine	SUS-Pt-Rh	CO, HC, NOx	50 & 100 cc	1/2, 1/3, 1/2	Jan.98	yes	10	
KSE, Inc., USA	stationary	SCR	NOx	1,000,000 h-1	90	94	N/A	6	\$49,975 contract, for European
Mazda Motor Co., Ltd., Japan	automobile	Pt-Ir-Rh-H- MF1(SiO2- Al2O3)	NOx	?	48.1- 51.7%	97	yes	22	
Nippon Puretec Co., Ltd., Japan	clean room	Clean Sorb chem. filter	VOC, O3, NO2 (10 to 50ppb)	?	90-94%	Nov'97	yes	17	O-type

List of Catalysts for Pollution Control

Company	Sources	Materials	Gases	Flow rate	De-%	Date	Commer.	Ref.	Comment
Nippon Puretec Co., Ltd., Japan	clean room	Clean Sorb chem. filter	HNO ₃ , HF (10 to 50 ppb)	?	90-94%	Nov'97	yes	17	H-type
	gas turbin	SCR	NOx (30-150ppm), SOx (0-30ppm)	?	-, 90	Jan'96	yes	18	gas temp. 180-450°C
Nippon Shokubai Co., Ltd., Japan	diesel engine	SCR	NOx (800-1500ppm), SOx (20-500ppm)	?	-, 90	Jan'96	yes	18	gas temp. 300-480°C SOF(Soluble Organic Fraction) catalyst
	oil boiler	SCR	NOx (100-200ppm), SOx (100-1500ppm)	?	-, 80	Jan'96	yes	18	gas temp. 280-400°C
	Industries air	STH catalyst	TCE	2,000hr-1	50-100	Jan'96	yes	18	gas temp. 250-350°C, initial conc. 1,000-2,500ppm
	Lean-Burn Gasoline engine	Cu-ZSM-5	HC/NO=5-10	45,000h-1	40-80	96	N/A	19	350-450°C
	diesel engine	Cu-ZSM-5	HC/NOx=5	55,000h-1	5-20	96	N/A	19	300-500°C
	diesel engine	TiO ₂ -SiO ₂ -V ₂ O ₅	urea/NOx=0.8mol	70,000h-1	50	96	N/A	19	300-500°C honeycomb type
	diesel engine(3% light oil)	Pt-Rh-Al ₂ O ₃	NOx	55,000h-1	20	96	N/A	19	200°C
	diesel engine(3% light oil)	Pd-Rh-Al ₂ O ₃	NOx	55,000h-1	20	96	N/A	19	350°C

List of Catalysts for Pollution Control

Company	Sources	Materials	Gases	Flow rate	De-%	Date	Commer.	Ref.	Comment
Osaka Gas Co., Ltd., Japan	gas turbine (city gas)	Cu-ZSM-5 (SiO ₂ /Al ₂ O ₃ 3=50, M ²⁺ /Al ₂ = 106%)	NO (500ppm) C ₃ H ₈ (1000ppm) O ₂ (10%) CO ₂ (6%) CO (1000ppm) H ₂ (660ppm)	?	40-70	96	N/A	25	300-600°C
	gas turbine (city gas)	Co-ZSM-5 (50,111%)	NO (500ppm) C ₃ H ₈ (1000ppm) O ₂ (10%) CO ₂ (6%) CO (1000ppm) H ₂ (660ppm)	?	40-100	96	N/A	25	300-600°C
	gas turbine (city gas)	Co- SiO ₂ /Al ₂ O ₃	NO (500ppm) CH ₄ (2500ppm) O ₂ (3.2%) CO ₂ (8.4%) H ₂ O (15.4%)	10,000h-1	57	96	N/A	25	550-570°C honeycomb type

List of Catalysts for Pollution Control

Company	Sources	Materials	Gases	Flow rate	De-%	Date	Commer.	Ref.	Comment
Osaka Gas Co., Ltd., Japan, & Eniricerche Co., Italy	gas turbine (city gas)	Co(3wt%)- Beta- (SiO ₂ /Al ₂ O ₃ 3=22.3)	NO (500ppm) C ₃ H ₈ (1000ppm) O ₂ (10%) CO ₂ (6%) CO (1000ppm) H ₂ (660ppm) H ₂ O(9%)	15,000h-1	54.7-83.7	96	N/A	25	400-600°C
	gas engine	Pt-Rh- Al ₂ O ₃	NO _x , CO, HC	?	?	May.96	yes	9	30,000hr no changeable
	C ₃ H ₆	Cu-Al ₂ O ₃	synthetic gas	15,000	30 (o% water), 10 (10% water)	Jul.96	bottle	12	bench test, HC/NO _x =5100ppmC/ 800ppm
	diesel fuel	Cu-Al ₂ O ₄	synthetic gas	15,000	30 (fuel), 50 (increased fuel)	Jul.96		12	bench test, 10% water, Max. Fuel/NO _x mass ratio=5
	diesel fuel	Cu-Al ₂ O ₅	diesel	?	30	Jul.96	spray system	12	Fuel/NO _x mass ratio=5
Riken, Japan	deisel engine	Ag-Al ₂ O ₃	NO (800ppm) SO ₂ (30ppm) O ₂ (10%) EtOH/NO (=3w/w) H ₂ O(10%)	40000h-1	8-80	97	N/A	24	250-450°C, honeycom type(2), by-products (THC = 25 ppm>, CH ₃ CHO=0,NH ₃ +other N-compounds=0, CO =10ppm>)

List of Catalysts for Pollution Control

Company	Sources	Materials	Gases	Flow rate	De-%	Date	Commer.	Ref.	Comment
Riken, Japan	diesel (light oil, S<0.2%)	EtOH over the Ag- Al ₂ O ₃	NOx (1300ppm) SO ₂ (20ppm)	50,000h-1	23-88	97	N/A	24	320-470°C honeycomb type
Selective Adsorption Associates, Inc., USA	Indesties air, hydrogen & other gases	carbons	Hg	10sec/area	<1 micg- Hg/Nm ³	?	yes	14	MERSORB®, Hg capacity 20Wt.% and Moisture content 3Wt.%Max.
	Industries water	carbon with chemical	Hg	?	ppMw of Hg	?	yes	14	MERSORB®, ref. show typical physical and chemical properties
SiemensAG, Germany	diesel, car	SCR	NOx, HC	?	70, 50-70	Dec.97	yes	1	SINOX system
South Coast Clean Air, Inc., USA	Industries air	catalytic oxidizers	VOC	?	?	?	?	15	
	Industries air	quench/scru b systems	NOx, SOx, HCl, H ₂ S	?	?	?	?	15	
Southwest Research Inst., USA	diesel	Cu-ZSM-5	adsorbed exhaust HC	20,000	50	Jul.96	N/A	12	no increased total HC emission
Southwest Research Inst., USA	diesel	Cu-Zeolite	Ethylene + exhaust HC	up to 30,000	50	Jul.96	bottle	12	particulate removal
	diesel	Cu- Mordenite	adsorbed exhaust HC	20,000	?	Jul.96	N/A	12	exhaust HCs can be used as reductants
Steuler, Germany	diesel	Zeolite- molecular sieves	?	?	?	82	100units	20	300-480°C
TDA Research, Inc., USA	automobile	metal oxide	H ₂ Cs, CO	?	98	94	N/A	7	\$50,000 contract
	automobile	SCR-CH ₄	NO, NOx	?	100	94	N/A	8	\$50,000 contract
Toyota Moter Co., Ltd, Japan	automobile	Pt(1.8wt%)- Ba-Al ₂ O ₃	NO (570ppm)	?	35-70%	94	yes	21	NSR catalyst

List of Catalysts for Pollution Control

1. <http://www.theautochannel.com/>, "Next-Generation Catalytic Converter for Diesel Engines Reduces Toxic Emissions by up to 70 percent", or <http://www.dieselnet.com/news/9712siemens.html>.
2. <http://www.catalytica-inc.com/news/news960411.html>, "Catalytica Awarded Contract with Allison Engine Company to Develop Catalytic Combustion for Next Generation Turbine".
3. http://www.catalytica-inc.com/cs/nox_control.html, "NOx control Options".
4. <http://www.clean.rti.org/serdp/COMP1A.htm>, "Metal Perovskite Catalysts for NOx Reduction".
5. <http://www.epa.gov/ncercq/sbir/93/phase1/topic5.html>, "5. Removal of Automotive Pollutants Using New Metal-Supported Metal Catalyst".
6. <http://www.epa.gov/ncercq/sbir/93/phase1/topic11.html>, "11. In-Duct Selective Catalytic Reduction of NOx".
7. <http://www.epa.gov/ncercq/sbir/93/phase1/topic15.html>, "15. Catalysts for the Control of Automotive Cold Start Emissions".
8. <http://www.epa.gov/ncercq/sbir/93/phase1/topic17.html>, "17. Selective Catalytic Reduction of NOx with Methane".
9. <http://www.osakagas.co.jp/Press/Html/p960416.htm>, written by Japanese.
10. <http://www.honda.co.jp/home/hpr/press-info98/c98011.html>, written by Japanese.
11. http://www.degussa.com/Chem_Catalyst/html/detail.html#StationaryEmission, "Stationary Emission Control Catalysts".
12. M.J. Heinrich, "Diesel NOx Catalytic Converter Development: A Review", *Transactions of the ASME*, 118, pp.668-672, (1996).
13. <http://www.aesinc.com/rto/rto2.htm>, "Regenerative thermal oxidation".
14. <http://selectiveadsorption.com/default.htm>
15. <http://www.quikpqge.com/S/sccair>
16. <http://www.inhs.uiuc.edu/isgroot/news/geonews/july95/act-char.html>
17. Air-Supply Chemical Filtration by Nippon Puretec Co. Ltd.
18. Product list by Nippon Shokubai Co., Ltd.
19. M. Horiuchi, "Catalytic NOx Reduction for Diesel Vehicle Exhaust", *Catalysis Society of Japan*, Vol.39, No.3 (1997)
20. M. Iwamoto et al., "Recent Progress in the Removal of NOx", *J. of Catalysis*, Vol.32, No.7 (1990)
21. S. Matsumoto, "NOx Storage-Reduction Catalyst for Lean-Burn Engine", *Catalysis Society of Japan*, Vol.39, No.3 (1997)
22. K. Komatsu, "A New Type of Three-Way Catalyst for LeanBurn Gasoline Engine", *Catalysis Society of Japan*, Vol.39, No.3 (1997)
23. T. Yoshinari, "Application of Alumina Catalyst to the NOx Removal from an Exhaust of Stationary Diesel Engine", *Catalysis Society of Japan*, Vol.39, No.3 (1997)
24. K. Yoshida, et. al., "Development of Ag/Al₂O₃ Catalysts for the Reduction of Lean NOx", *Catalysis Society of Japan*, Vol.39, No.3 (1997)
25. T. Tabata et. al., "Catalysts for the Selective Reduction of NOx for the Purification of Natural Gas Combustion Exhaust", *Catalysis Society of Japan*, Vol.39, No.3 (1997)

REPORT DOCUMENTATION PAGEForm Approved
OMB No. 074-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503

1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE October 31, 1998	3. REPORT TYPE AND DATES COVERED Final Report	
4. TITLE AND SUBTITLE Development of Scaling Algorithms and Economic Evaluation for Non-Thermal Plasma Reactors - Adsorbant/Catalyzer Hybrid System for Control of Nox Released During Army and Related U.S. Department of Defense (DOD) Operations			5. FUNDING NUMBERS N/A	
6. AUTHOR(S) K. Urashima, S.J. Kim and J.S. Chang				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Department of Engineering Physics, McMaster University Hamilton, Ontario, Canada L8S 4L7			8. PERFORMING ORGANIZATION REPORT NUMBER N/A	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) SERDP 901 North Stuart St. Suite 303 Arlington, VA 22203			10. SPONSORING / MONITORING AGENCY REPORT NUMBER N/A	
11. SUPPLEMENTARY NOTES No copyright is asserted in the United States under Title 17, U.S. code. The U.S. Government has a royalty-free license to exercise all rights under the copyright claimed herein for Government purposes. All other rights are reserved by the copyright owner.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release: distribution is unlimited.				12b. DISTRIBUTION CODE A
13. ABSTRACT (Maximum 200 Words) Computer code (SUENTP-J) to predict scale-up and economic evaluation of several eligible non-thermal plasma processes for air pollution control – electron beam process, pulsed corona process, and corona radical shower process – was developed for a commercial power plant. This code was written in spread sheet type format (MS Excel) and visual basic for application and comprise a data input procedure, a scale-up (design) procedure, an economic calculation procedure, and an output procedure. Data obtained from pilot plant tests are input with general data so that they might lead to the conceptual design data of commercial plants by scale-up procedure. In the economic evaluation procedure, the total capital investment and the total annual cost are examined. The total capital investment comes into the indirect annual cost as the item of capital recovery. The levelized cost and the levelized busbar cost are shown in the output table. An example calculation was presented to evaluate the cost of three non-thermal plasma systems and the results were compared with a conventional wet-scrubber/selective catalytic reduction combined system.				
14. SUBJECT TERMS SERDP, SUENTP-J, non-thermal plasma reactor, jet engine, gas emission				15. NUMBER OF PAGES 69
				16. PRICE CODE N/A
17. SECURITY CLASSIFICATION OF REPORT unclass	18. SECURITY CLASSIFICATION OF THIS PAGE unclass	19. SECURITY CLASSIFICATION OF ABSTRACT unclass	20. LIMITATION OF ABSTRACT UL	